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Research Report No. 56 Design and Performance Criteria for Settling

Design and Performance Criteria for Settling Tanks for the Removal of Physical-Chemical Flocs

Volume II

Research Report No. 56

arch Program for the Abatement of Municipal Pollution under Provisions of the Canada-Ontario Agreement on Great Lakes Water Quality

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These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Fisheries and Environment Canada, and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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DESIGN AND PERFORMANCE CRITERIA FOR SETTLING TANKS FOR THE REMOVAL OF PHYSICAL-CHEMICAL FLOCS

VOLUME II

by

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RESEARCH PROGRAM FOR THE ABATEMENT OF MUNICIPAL POLLUTION WITHIN THE PROVISIONS OF THE CANADA-ONTARIO AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

The objective of this research was the study of settling behaviour of physical-chemical suspensions, on both a laboratory and plant basis, in order to suggest design guidelines and methods to predict the performance of settling tanks treating such suspensions.

A brief literature review confirmed the belief that relatively little work on this topic had been carried out, although there was much pertinent background material available. Laboratory studies under quiescent settling conditions and plant studies have been carried out during the past three years at Toronto, Sarnia, Windsor and the Wastewater Technology Centre in Burlington. The addition of coagulants (ferric chloride, alum and polymer) to domestic wastewater for the primary purpose of phosphorus removal has an important side effect in increased suspended solids and BOD removal. In addition, this study shows that flow rates can be increased substantially, thus increasing the capacity for existing settling tanks.

Tentative guidelines have been suggested for the design of settling tanks. The use of these guidelines will result in smaller settling tanks that would be required by the current guidelines. The cost savings for the expansion of existing plants and the construction of new settling tanks are expected to be significant.

RÉSUMÉ

La présente recherche porte sur la décantation, en laboratoire et en usine, des liquides contenant des particules physico-chimiques en suspension; elle a pour but de dégager des lignes directrices et des méthodes de conception permettant de prévoir le rendement des bassins de décantation qui retiennent ces matières en suspension.

Une brève étude bibliographique a corroboré le sentiment assez répandu que relativement peu de travaux ont déjà porté sur le sujet, même si de nombreux documents informatifs sont accessibles. Des études en laboratoire, faites dans des conditions de décantation dormante, et d'autres études en usine ont été effectuées au cours des trois dernières années à Toronto, Sarnia, Windsor et au Centre technique des eaux usées de Burlington. L'addition de substances coagulantes (chlorure ferrique, alun, polymères) aux eaux usées domestiques pour en éliminer le phosphore a un important effet secondaire: une réduction accrue des particules en sus- pension ainsi que de la DBO. En outre, la présente étude montre que le débit du traitement peut augmenter considérablement, la capacité des bassins de décantation existants s'en trouvant accrue.

Des lignes directrices provisoires pour la conception des bassins de décantation, remplaçant celles qu'on applique actuellement, pourraient amener une réduction de la taille des bassins. Cela pourrait permettre des économies notables quand il y aura lieu d'agrandir les usines actuelles et de construire de nouveaux bassins de décantation.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

σ^2	- variance of C-Curve (dimensionless)
a	- constant in the dispersion model
A	- constant of wastewater characteristics
b	- constant in the dispersion model
c_o	- dose of tracer per unit volume of settling tank
c	- tracer concentration in time 't'
C_x	- eddy coefficient in the direction of flow
C_z	- eddy coefficient in vertically downward direction
d	- constant in the dispersion model
d'	- dispersion index
D	- depth of settling tank (m)
e	- hydraulic efficiency index of settling tank, tg/T
F	- overflow rate
ft	- feet
gpd	- gallons per day (Imperial)
H	- depth of baffle board (or centre ring) below the water surface (m)
k,k'	- flocculation constants
K_1, K_2, K_3	- constants in dispersion model
l	- litres
m	- metres
mg	- milligrams
mm	- millimetres
M	- constant in the dispersion model
MGD	- million gallons per day (Imperial)
n	- flocculation constant
N	- constant in the dispersion model
p	- constant
Q	- suspended solids loading (kg/day)
r	- constant
S_o	- suspended solids in influent to the settling tank, mg/l
S	- suspended solids in effluent, mg/l
t	- time in minutes

LIST OF SYMBOLS AND ABBREVIATIONS (CONT'D)

U	- mean velocity (mm/sec)
V'	- eddy velocity in the horizontal direction of flow (mm/sec)
$\overline{V}$	- mean eddy velocity (mm/sec)
W'	- eddy velocity in vertically downward direction (mm/sec)
$\overline{W}$	- mean eddy velocity (mm/sec)
X	- coordinates in the horizontal direction of flow (m)
Y	- coordinates across the settling tank (m)
Z	- coordinates in the vertically downward direction (m)

1 INTRODUCTION

Sedimentation has been used for a very long time to remove suspended solids in the treatment of water and wastewater. Settling tanks account for a substantial part of the construction cost of treatment plants, yet surprisingly little research has been carried out in recent years to improve our knowledge of the principles and practice of the settling process. Conventional design criteria of overflow rate (or surface loading) and detention time have been used for many years. The criterion of overflow rate provides a theoretical basis for the settlement of discrete particles. However, most practical suspensions are flocculent, so that settling tests are required. For 'known' suspensions, such as domestic wastewater or raw water for drinking water supply, 'rule of thumb' design figures have been established over many years.

The recent emphasis on phosphorus removal from wastewater has brought about the widespread use of chemicals (coagulants/precipitants) in wastewater treatment. The addition of these chemicals to wastewater results in suspensions of a different nature, which have different settling characteristics than physical or physical-biological suspensions. The main objective of this research program was to establish settling behaviour of physical-chemical suspensions and to suggest design guidelines for settling tanks treating such suspensions.

The rate of settling of a suspension in a settling tank depends on the settling characteristics of the suspended particles or flocs and on the hydraulic characteristics of the tank. Removals achieved in a settling tank will normally be considerably lower than those achieved under quiescent conditions in a long-tube settling test because of short circuiting, tubulent conditions, sludge resuspensions, density currents and other reasons. Much work has been done in the past to decrease these undesirable effects.

Several researchers have attempted to develop mathematical models for various phenomena of the sedimentation process such as settling of discrete particles, flocculation, short-circuiting and turbulence in flow, etc., on the basis of laboratory scale experiments using mostly artificial suspensions. Some models are simple in form while others are

fairly complex, but none can reasonably depict the settling behaviour of real suspensions in real tanks, particularly when chemical treatment is practised.

2 SUMMARY OF FINDINGS

The conclusions and recommendations derived from this study are based on the results obtained in the laboratory and at the treatment plants at Sarnia and Windsor, and the pilot plant at Burlington. These plants have settling tanks of different sizes and shapes (rectangular and circular). The reasonably consistent results indicate that these findings may be applicable to other plants. It is, however, recommended that these should be tested in other plants.

The findings can be summarized as follows:

1. Clarification efficiency of settling tanks depends on settling characteristics of suspensions and hydraulic behaviour of settling tanks.
2. The performance of settling tanks can be predicted with reasonable accuracy from settling column tests and tracer studies; the combined effects of these are presented as an empirical settling model.
3. The settling behaviour of suspended solids in the settling tank may also be predicted by a dispersion model developed in this study.
4. Chemical addition (alum or ferric chloride) increases settling rates of flocs and considerably improves effluent quality. Addition of polymer (Dow Purifloc A23), in combination with ferric chloride or alum, further increases settling rates and, consequently, effluent quality.
5. Under quiescent conditions most of the settling of suspensions in domestic wastewater occurs in 45 minutes with no chemical, 30 minutes with ferric chloride (or alum), and 15 minutes with ferric chloride (or alum) plus polymer addition.
6. The performance of the settling tank for domestic wastewater depends primarily on the actual mean detention time of the tank. Overflow rate, within the range of the studies (up to about 2000 gpd/ft^2 or 100 m^3/m^2/day) does not have a significant effect on the quality of effluent, particularly when chemicals are added. This means that

any two tanks treating similar suspensions are expected to produce effluents of approximately the same quality if actual mean detention times of both tanks are equal (even though overflow rates may be different). On the other hand, two tanks are expected to produce effluents of different quality if actual mean detention times are different (even though overflow rates may be equal).

7. As the rate of flow through the settling tanks increases, effluent quality deteriorates in response to decreasing detention time.
8. The rectangular tanks at Sarnia produce a good effluent. Their performance is much better than the circular tanks at Windsor.
9. The settling tanks tested perform both as flocculating and settling tanks. The turbulence in tanks helps improve the formation of flocs and, consequently, their settling rates. The addition of flocculating devices near the inlet end of settling tanks may prove to be beneficial.
10. No special attempt was made to study the effects of temperature on settling. However, the data collected in summer and winter did not show any significant difference.
11. Settling column tests showed that alum and ferric flocs have similar settling behaviour. So far, only the effects of ferric chloride (with and without polymer) addition have been checked out on a plant-scale basis. Similar performance, is, however, expected with the addition of alum as well.

2.1 Empirical Models

Two different models have been developed which use two different concepts and techniques to predict the performance of a settling tank:

A. Settling Model:

From settling column and tracer studies (with the limitations described later under "Design Guidelines"):

$$S = \frac{S_o A}{(eT)^n + A} \qquad \text{and } e = \frac{t_g}{T}$$

where: S_o - suspended solids in influent to settling tank, mg/l,

S - suspended solids remaining in effluent, mg/l,

tg - actual mean detention time in minutes,

T - theoretical detention time of settling tank in minutes,

e - hydraulic efficiency index of settling tank developed from tracer studies,

n & A - constants of wastewater characteristics developed from settling column tests.

- The values of constants 'n' and 'A' for domestic wastewater, with and without chemical addition, are given in Section 11.
- The hydraulic efficiency index 'e' is expected to vary from tank to tank, depending upon the shape, size and hydraulic and functional design of settling tank. The value of the index should be determined by tracer studies.

B. Dispersion Model:

This is based on a model developed in the air pollution field to predict the dispersion of particulate matter from stack emissions, which was modified for settling tanks.

$$S = \frac{K_1 \; Q^d EXP(-Y^2/C_x{}^2 X^a)}{C_x C_z U \; X^a} \left[EXP\left(\frac{{}_2 \; (Z-H)}{C_z{}^2 \; X^b}\right) + EXP\left(\frac{K_3 \; (Z+H)}{C_z{}^2 \; X^b}\right) \right]$$

where:

C_x - eddy coefficient in flow direction,

$$= \left[\frac{M}{U^N} \left(\frac{(V')^{\;2}}{U^2} \right)^{1-N} \right]^{\frac{1}{2}}$$

C_z - eddy coefficient in vertical direction,

$$= \left[\frac{M}{U^N} \left(\frac{(W')^{\;2}}{U^2} \right)^{1-N} \right]^{\frac{1}{2}}$$

S - concentration of suspended solids (mg/l),

Q - suspended solids loading (kg/day),

X,Y,Z - coordinates measured respectively, horizontally in the direction of flow, across the tank, and vertically downward (m),

H - depth of baffle board (or centre ring) below the water surface (m),

U - mean velocity (mm/sec).

V', W' - eddy velocities in flow (horizontal), and vertical directions respectively (mm/sec),

K_1, K_2, K_3 - constants,

N, M, a, b, d - constants.

- The solution of the model for domestic wastewater, with ferric chloride plus polymer addition is given in subsection 10.2.2.
- With the measurement of velocity and suspended solids profiles, it is possible to calculate the parameters in the dispersion model, and thereby predict solids concentration in the effluent and in the tank. However, further work is required on the dispersion model before it may become a useful tool. (This work is presently being carried out under a separate project).

2.2 Tentative Design Guidelines

The following tentative guidelines are proposed for the design of primary clarifiers (horizontal flow clarifiers) treating domestic wastewater:

Design flow rate: Maximum daily flow (normally 1.5 - 2.0 x average daily flow).

Actual mean detention time (t_g):

30 minutes with chemical addition (ferric chloride plus polymer),

45 minutes without chemical addition.

Minimum detention time (t_{10}):

(t_{10} = time interval before 10% of quantity of the tracer added passes over the weir)

15 minutes with chemical addition (ferric chloride plus polymer),

30 minutes without chemical addition.

Overflow rate:	less than 2000 gpd/ft^2 (100 $m^3/m^2/day$) under peak flow conditions.
Velocity:	less than 8 ft/minute (40 mm/sec) under peak flow conditions.
Removal efficiency:	about 70% with ferric chloride addition,
	about 85% with ferric chloride plus polymer addition,
	about 40-50% without chemical addition.

Laboratory results and limited plant results on alum indicate that the above design guidelines may also be applicable for alum addition.

It is beyond the scope of this report to make recommendations regarding the geometric design of settling tanks (shape, length/width/depth or diameter/depth ratios, types and positions of baffles and weirs, etc.). The problem remains, therefore, how to choose actual tank dimensions to achieve a required actual detention time.

The use of these tentative guidelines will result in smaller settling tanks than would be required by current guidelines. The extent of the decrease in size will depend on the hydraulic efficiency, e, which was previously defined as the ratio of actual mean detention time to theoretical detention time. The hydraulic efficiency of tanks studied under varying flow rates ranged from 0.30 (circular tank at Windsor) to 0.78 (rectangular tank at Sarnia).

2.3 Cost Savings by Chemical Addition

Chemical treatment is coming into widespread use, primarily for the removal of phosphorus from wastewaters. This study has revealed that such chemical addition has considerable secondary benefits. The study showed that chemical addition causes suspensions to settle faster, and that, consequently, significantly smaller settling tanks are required for their removal than without chemical addition. Furthermore, with chemical addition higher and more reliable removal efficiency of suspended solids and BOD, as well as phosphorus, is achieved.

If the findings of this study are found to be applicable generally, chemical treatment will result in considerable savings in capital costs which, in turn, will offset part or all of the operating cost of chemical

addition. For existing plants, chemical addition will substantially increase the capacity of the settling tanks, which will avoid or delay the need for expansion. In some cases, effluent quality may be good enough to allow discharge into receiving waters without secondary treatment.

3 SCOPE OF STUDY

This report covers research studies carried out over a period of about three years (July 1972 to March 1975) under annual contracts. The first phase of the program was reported in Canada-Ontario Agreement Research Report No. 10 (Heinke, 1973). It includes a brief literature review, laboratory studies at Toronto and a field study at the Sarnia Sewage Treatment Plant. Subsequent work has been covered in Progress Reports (October 1973, May and October 1974) which have not been published.

For completeness, this report covers all the work carried out, but makes reference to the previously published report where appropriate. It should be read together with this report for complete coverage.

The work performed under the program essentially falls into the following categories:

a) The study of settling characteristics of physical-chemical flocs under quiescent conditions in settling columns.
b) The study of hydraulic behaviour or rectangular and circular settling tanks.
c) The study of settling characteristics of physical-chemical flocs, on plant-scale basis, in settling tanks under variable flow conditions.
d) The development of an empirical model to describe the relationship between the settling characteristics of physical-chemical flocs and the hydraulic behaviour of settling tanks, with and without chemical addition, and under various hydraulic loadings.
e) The development of an empirical dispersion model to study the effects of turbulence and velocity in the settling performance of the tanks.
f) The formulation of design guidelines.

A brief outline of the various phases of the study follows.

3.1 Literature Review

A brief literature search was conducted in 1972 to collect background information which could be directly or indirectly useful to the topic under study. The review of the literature was included in the first

report (Heinke, 1973). Some additional articles relevant to this study are reviewed in this report, and the complete bibliography has also been updated and is included.

3.2 Laboratory Studies at the University of Toronto

Laboratory studies were carried out on wastewater brought from the Humber Sewage Treatment Plant, with and without chemical addition. About 50 long and short tube settling tests were conducted, with additional jar testing, thickening and specific resistance tests on somewhat fewer samples. Some of this work was carried out prior to award of the contract.

The Sarnia and Windsor Sewage Treatment Plants were chosen for further laboratory and plant studies because they were primary plants practicing, or about to practice, chemical treatment, and because they were anxious to cooperate.

3.3 Field Studies at Sarnia

a) Plant Performance Evaluation

Plant performance data for the years 1971 and 1972 were analyzed statistically using the flow rate and suspended solids, BOD and phosphorus in the influent and effluent of the plant as parameters. Data taken by others (The City of Sarnia, Ontario Ministry of the Environment and Dow Chemical Co.) on the effect of the addition of chemicals (ferric chloride, alum and polymer) were studied in relation to various overflow rates (300 to 800 gpd/ft^2 or 15 to 40 m^3/m^2/day).

b) Settling Column Tests

Fifty-nine settling column tests were performed to study the settling behaviour of suspended solids, with and without chemical addition. In this study, the chemicals (ferric chloride, alum with and without polymer addition) were mixed in the plant, and the samples were taken up at the inlet of the settling tank and allowed to settle in a long tube under quiescent conditions in the plant laboratory.

c) Tracer Studies

Fifty dye tests were performed to study the hydraulic behaviour of the settling tanks (rectangular). Various hydraulic parameters,

and dispersion and short-circuiting indices were evaluated, with and without chemical addition, under various hydraulic loadings (700 to 2200 gpd/ft^2 or 35 to 110 m^3/m^2/day). The variation of flow rate was obtained by running the plant on three, two, and one settling tank. These tests were carried out in summer as well as in winter.

d) Suspended Solids and Velocity Profiles

In-plant study of the settling behaviour of suspended solids was carried out by measurement of suspended solids concentration and velocities in the settling tank on a three-dimensional grid system. In all, 33 sets of measurements were taken under various conditions of chemical treatment and hydraulic loading.

3.4 Field Studies at Windsor

a) Plant Performance Evaluation

Plant performance data for the years 1971 and 1972 were analyzed statistically in the same manner as for the Sarnia Treatment Plant. This provided information for comparison of the performance of the long rectangular tank in Sarnia with the circular tank in Windsor.

b) Settling Column Tests

Seventy settling column tests were performed for quiescent settling analysis along the same lines as in Sarnia.

c) Tracer Studies

Twenty-six dye tests were carried out to study the hydraulic behaviour of the circular settling tank. Various hydraulic parameters, and dispersion and short-circuiting indices, were evaluated under various hydraulic loadings. Dye measurements were also taken in the settling tank at various depths and locations to trace the flow paths and to determine the dead zones in the tank.

d) Suspended Solids and Velocity Profiles

Suspended solids and velocity measurements were taken at four different locations and at five different depths along the radius of the circular tank. In all, 45 sets of measurements were carried out under various conditions of chemical treatment and hydraulic loading.

3.5 Pilot Plant Studies at WTC, Burlington

In Sarnia and Windsor it was difficult to maintain steady flow conditions in the settling tanks. The flow through the tanks varied (to a small extent during the day time) in response to changes in flow rate of influent from the city. The pilot plant in Burlington had facilities which allowed the overflow rates to be maintained steadily within a certain range. To obtain data under steady and stable conditions, studies similar to those carried out in Sarnia and Windsor were peformed. The extent of the work was as follows:

a) Forty jar tests were carried out to determine optimum chemical type and dosages for phosphorus removal.

b) Some 80 tests were performed for measurement of suspended solids and velocity profiles at various overflow rates, with and without chemical addition.

c) Twenty-one dye tests were performed to study the hydraulic behaviour of the settling tank.

d) The characteristics of influent and effluent were determined throughout the study period (June to mid-August, 1974) by the measurement of suspended solids, BOD, COD, TOC, and total phosphorus, with and without chemical addition.

e) Ten settling column tests were peformed to determine the settling characteristics of Burlington wastewater in comparison with wastewaters in Sarnia and Windsor.

4 LITERATURE REVIEW

A brief literature search was conducted in 1972 reported in the first report (Heinke, 1973). A summary of some of the articles reviewed during the last two years in the areas related to this study is given below. An updated bibliography has also been included in this report.

Hazen (1904), from his study of the sedimentation process, concluded that sedimentation is dependent upon the area of bottom surface exposed to receive sediment, and that it is entirely independent of the depth of the basin. He further pointed out that the best results can be obtained when the basins are so arranged that the incoming water containing the maximum quantity of sediments is kept from mixing with water which is partially clarified.

Camp (1945) discussed the known principles of sedimentation essential to the development of design theory, and extended them to a stage which could have more practical value. Much of the subject matter is the work of others. By analyzing the various factors involved with the sedimentation process, he could emphasize that the settling performance of clarifiers depends mainly in the settling characteristics of the suspensions and overflow rates. He further pointed out that an increased removal of flocculating suspensions should be expected from tanks with higher velocities than are commonly used, if sludge bed scouring is avoided. This led to the conclusions that depth might have insignificant effect on settling of flocculating particles.

Camp (1953) reviewed the principles of sedimentation tank design based on bottom area as propounded by Hazen (1904), and also discussed the effects of flocculation, turbulence, short-circuiting and stability on the performance of a sedimentation tank.

Fischerstrom (1955) pointed out the primary importance of a sedimentation basin's good hydraulic properties in the prevention of disturbances. He further emphasized the importance of good 'inlets' and 'outlets' and, especially, the desired stability and turbulence of flow in the basins. From his study he concluded that most of the basins with unstabilized flow will show great variations in settling efficiency. At higher Froude Number the sedimentation performance is more stable than at

lower Froude Number, and the sedimentation efficiency improves when the flow is divided into a number of parallel compartments.

Fitch (1956) proved by a mathematical model that sediment removal is a function of the settling rate of particles and overflow rate only, regardless of the direction, magnitude and variation in depth of flow itself. He further concluded that removal efficiency is not affected by density currents or the shape of tank, provided that the influent is uniformly distributed and that the effluent is drawn uniformly over the entire length of effluent weir. The lack of distribution of flow laterally can seriously affect removal efficiency.

Clements (1966) studied the effect on settling efficiency of variation in velocity over the depth and the width of a rectangular tank. He emphasized that the horizontal velocity variations across the width of a rectangular tank seriously affect settling efficiency, whereas velocity variations in depth have little effect on sedimentation if scour is avoided. He introduced the term 'time ratio' (the ratio of effective flow-through time to effective settling time) as a parameter to measure the settling efficiency of tanks. From experimental results he also concluded that the ratio D/D_i (depth of flow to depth of inlet section) is an important factor in settling tanks. The time ratio can be improved by lowering D/D_i ratio.

Clements and Khattab (1968) extended the 'time ratio' theory (as defined above) to circular settling tanks.

Price (1974) supported the 'time ratio' theory propounded by Clements (1966).

Price and Clements (1974) studied the effects of inlet changes, density and wind-induced currents on the performance of rectangular sedimentation tanks in both a model and a full scale basis. They also tested the importance of 'time ratio' as a parameter to measure the settling efficiency of basins. From their work they concluded (a) that considerable variations in 'time ratio' values can exist in rectangular sedimentation tanks, and that a higher time ratio leads to high suspended solids removals in the same tank with the same sewage, (b) that the time ratio can be changed by variations in the inlet, (c) that, unless scouring is caused, winds blowing along the tank length (either upstream or downstream) are likely to cause much less variation in removal performance than winds in a direction across the flow.

Villemonte et al (1967) developed a criterion called 'critical settling depth' by matching the settling rate of suspensions at various depths and the removal performance of the laboratory model of settling tank, using aluminum hydroxide flocs.

Chiu (1974), from theoretical flow characteristics, proved that the flow in circular tanks tends to be unstable which results in serious eddy currents. This condition of flow makes circular tanks inefficient in comparison with rectangular tanks.

Feurstein and Selleck (1963) studied the characteristics of three common tracers: Pontacyl Brilliant B, Rhodamine B and fluorescene. They concluded that none of these tracers are perfect. However, Pontacyl Brilliant B is the most suitable quantitative tracer for applications in natural stream water.

Murphy (1963) suggested the use of "Index of Short-Circuiting" to determine the efficiency of a settling tank.

Thirumurthi (1969) suggested the use of "Dispersion Index" as the performance parameter for sedimentation tanks. He stated that the Dispersion Index is more reliable than the Index of Short-Circuiting because a larger number of points are included in calculating the index and it is reproducible under similar conditions.

Fielder and Fitch (1959) derived mathematical functions for evaluating flocculent settling in sedimentation basins by means of dye tests. They concluded that "standard detention efficiency" as calculated from the dye test is a reasonable measure of the effectiveness of a settling basin.

Voshel and Sak (1968), in a plant-scale study, developed an empirical relationship among suspended solids removal, feed loading and overflow rate, with and without the addition of polymer (Purifloc A-21, a product of Dow Chemical Co.).

The following articles relate to the mathematical modelling of settling behaviour of particles in water and air:

Dobbins (1944) derived the general differential equation which expresses the concentration changes during turbulent sedimentation.

McLaughlin (1961) solved the differential equation to describe the flocculent settling in turbulent sedimentation.

Wnek and Fochtman (1972) measured the BOD at different locations in a river, and solved the differential equation for evaluating the rate of change of a pollutant in the turbulent river.

The theory of eddy diffusion in the atmosphere was first expounded by Taylor (1915). He measured temperature distribution together with wind velocity and direction in height by kites. From this information he was able to prove that the vertical transference of heat in the atmosphere is mainly governed by eddies.

Taylor (1922) statistically derived a correlation coefficient which expresses the turbulence diffusion phenomenon. The correlation coefficient is sufficient to determine the law of diffusion which governs the average distribution of particles initially concentrated at one point.

Sutton (1932, 1934, 1947) adopted Taylor's statistical theory of turbulence, and developed a set of equations for the diffusion of gases from different types of sources. He introduced the ideal of an effective eddy, which, he stated, governs the rate of diffusion. Later, he derived a diffusion coefficient to represent the effective eddy. This diffusion coefficient depends primarily upon the value of n (coefficient of mixing power of turblence) and the magnitude of fluctuating wind velocity, and only slightly upon mean wind velocity.

Baron et al (1949) modified Sutton's equation by taking into account the finite settling velocity of aerosol particles. He developed a method to approximately estimate the deposition of aerosol particles from the modified equation. He concluded that the modified equation gave a reasonable picture of the deposition of aerosol particles. He also estimated that increase in turbulence greatly decreased the rate of deposition and the ground concentration.

Bosanquet et al (1950) developed a set of simple formulae and charts to predict the path of particles emitted from a stack and spread by wind. They applied experimental checks to estimate the accuracy of formulae and concluded that it would not be possible to predict the rate of deposits within a factor of two by their formula.

Turner (1964) measured SO_2 concentration at 32 locations in a 17 x 16 mile rectangular urban area, and developed a multiple sources diffusion model for determining the spatial pollutant concentration. When

the observed values were compared with the calculated model values, only 58% were within $\pm$ 1 pphm (parts per hundred million). When zero values of both calculated and observed concentrations were excluded, 70% of the calculated values were within a factor of 2 of the observed values. Turner pointed out a number of sources of error.

Leahey (1972) used a simple air pollution model to test SO_2 data collected at New York City. The model was nondiffusive and relied primarily upon conservation mass. He defined a mixing ratio to verify the model. The mixing ratio was the ratio of amount of pollutant emitted to the wind speed, mixing depth and density of the air. He found that the predicted SO_2 mixing ratio agreed well with the observed value, with a correlation coefficient of 0.83.

Hino (1963) derived the energy equation for turbulent flow with suspended particles as well as the acceleration balance equation of turbulent motion. From the former equation, he predicted that Von Karman's constant (which indicates the characteristics of normal turbulent motion) invariably decreases with increasing particle concentration. This agreed fairly well with experimental results from other researchers. He also predicted that for flows with nearly neutrally-buoyant particles, turbulent intensity could increase with increased particle concentration, and that it would decrease gradually as particles density deviated from that of liquid.

By studying the dispersion process on triangular and circular arc cross-section channels, Sooky (1969) developed equations and diagrams to relate the dispersion coefficient, width/depth ratio, cross-section geometry and the Reynolds number of the channel. Sooky applied them to a natural stream with an irregular cross section, and found them in close agreement with the observed results. He concluded that only cross sectional geometry and mean flow velocity are required for determining the dispersion phenomenon in natural streams.

Apmann and Rumer (1970) investigated the diffusion of discrete sediment particles in a developing flow using the simplified convective-diffusion equation as a mathematical model. He performed the experiments in a 24-ft-long flume with three different sediments to determine the diffusion coefficients. He found that a simplified convective-diffusion equation was adequate to describe the measured sediment concentration profiles. He also stated that the vertical sediment mass diffusion

coefficients varied near the beginning of the flow, and tended towards uniformity as downstream distance increased. The diffusion rate varied with the depth of channel as a power law function.

Jobson and Sayre (1970) obtained the numerical solution of a two-dimensional mass transfer equation for dispersion in open channel flow. The solution was shown to adequately represent the dispersion process when it was compared with laboratory data obtained in a large flume. He concluded that the particles' fall velocity controls the rate of descent of the dispersant mass, but has little effect on the rate of spread of the dispersant. The magnitude of the transfer coefficient controls the rate of spread of the dispersant, but has little effect on its rate of descent.

Bansal (1971) developed a one-dimensional and a three-dimensional model to study the dispersion characteristics of the natural stream. He verified his models by dye study on the Mississippi River. From the models he derived three dispersion coefficients in the three spatial directions, and he assumed that these coefficients are constant throughout the stream. Once the dispersion coefficients are known, the time concentration distribution of a conservative pollutant can be determined at any point in the stream from the models.

Crickmore (1972) performed tracer studies on both a prototype tidal channel and a hydraulic model to investigate the turbulent diffusion process. He found that the spatial distributions of tracer concentration are probability density functions and are essentially Gaussian in all directions, and that the diffusion process is governed by Fick's law of diffusion.

McQuivey and Keefer (1974) performed dye tests on 18 natural streams and developed a simple method to predict the longitudinal dispersion process. They stated that the dispersion coefficient can be predicted from existing basic hydraulic and flow parameters by their method, with standard error of approximately 30%.

5 METHODOLOGY

The following procedures have been adopted to carry out various studies and analyses.

5.1 Settling Column Tests

In this test a column of uniformly mixed dilute suspension was allowed to settle under quiescent conditions in a long tube, seven feet (2.13 m) in length, six inches (0.15 m) in diameter. Samples of wastewater were taken at suitable time intervals from the sampling ports which were provided at one foot (0.30 m) depth intervals. Samples were then filtered to find out the concentrations of suspended solids for various detention times, and at various depths of water. From this information a 'design graph' was developed which related suspended solids removal for given overflow rates and detention times. For details see Qazi (1972).

5.2 Tracer Studies

Tracer studies have been conducted to determine the actual detention time and the hydraulic behaviour of the settling tanks. The pulse technique has been used throughout the study.

A known quantity of Rhodamine B was dumped at the inlet to the clarifier, and samples were collected at the effluent weir by a low-head continuous pump and delivered directly to the Fluorometer (G.K. Turner Associates, Model III). Dye concentration was determined by using a No. 1-60 and No. 58 primary filter and a No. 23-A secondary filter (Wallace 1965, Fluorometer Operating and Service Manual), and was continuously recorded. Prior to field tests, the equipment was calibrated according to standard procedures.

Fluorescence readings can be affected by a change in suspended solids concentration and temperature. It is therefore necessary to prepare different calibration curves for different suspended solids ranges and seasonal conditions.

5.3 Local Velocity Measurements at Sarnia

The velocity was measured by a Low Velocity Current Meter, manufactured by Ontario Hydro, with a Heathkit Digital Multimeter. The meter was calibrated in the laboratory of Ontario Hydro (Toronto) before

it was used in the field and was rechecked after the field studies. The meter could measure only nondirectional composite velocity at a point.

To carry out this study, a three-dimensional grid system was established in the settling tank: five cross-sections of the tank at 15, 35, 55, 85, and 110 ft (4.5, 10.5, 16.5, 25.5 and 33.0 m) from the inlet wall were selected, and then sixteen points (four across x four depths) were chosen at each section for taking measurements. This meant that 160 readings, i.e., 80 for suspended solids (see last sub-section) and 80 for velocity measurements, were required for each experiment. The readings for suspended solids and local velocities were taken one after the other and the work proceeded in the direction of flow. With this number of readings it was possible to proceed with the flow, and readings were supposedly taken from the same bulk of wastewater as it proceeded towards the effluent channel. The number of readings was cut down to 80 (8 points at each cross-section) when only one tank was in operation.

To take the reading, the sensors were lowered to the point of interest in the tank and the reading of the voltmeter was recorded after it was steady. When the readings fluctuated due to the unsteady flow conditions in the tank, average readings were used. The voltmeter readings were transformed into velocity by calibration curve provided by Ontario Hydro.

5.4 Local Velocity Measurements at Windsor and Burlington

The velocity was measured by a directional low velocity current meter (Electromagnetic Water Current Meter, 600 Series Velmeter, Model P, manufactured by Cushing Engineering Incorporated) which used a two-axes automatic recorder, 'Servocorder SR652-2H' manufactured by the Watanabe Instrument Corporaton, Tokyo, Japan. The meter could record velocity in any direction, and in two directions, perpendicular to each other, simultaneously if so desired.

In Windsor, velocity measurements were taken at five different depths (2, 4, 6, 8, and 10 ft or 0.6, 1.2, 1.8, 2.4, and 3.0 m), and at four different locations (15, 30, 45, and 50 ft or 4.6, 9.2, 13.7, and 15.3 m from the centre) along the radius of the tank.

In Burlington, velocity measurements were taken at six different depths at 1.0 ft (0.3 m) intervals, and at three different locations (1.8, 2.4, and 3.2 ft or 0.5, 0.7, and 1.0 m from the centre) along the radius of the tank.

To take readings, the sensor was lowered to the point of interest in the tank, while facing the electrode in the direction for which the velocity measurement was required. The readings were recorded.

5.5 Local Suspended Solids Measurements

Suspended solids measurements were taken by a Suspended Solids Monitor manufactured by Par-Tech, on the three dimensional grid system for the rectangular tank, and along the radius at various depths and locations for the circular tank as described above. The solids were detected by the electronic cell of the meter and registered by the recorder. Prior to the field tests, the meter was calibrated in the laboratory according to recommended procedure.

Different calibration curves were prepared for chemical and nonchemical addition. The meter calibration was checked every day by gravimetric method.

6. FUNCTIONAL AND PERFORMANCE DATA OF TREATMENT PLANTS

For the objective of this research program, it was desirable to work at plants which treated mainly domestic wastewater, practised chemical treatment, had reasonable laboratory facilities, had the ability to vary the overflow rate to settling tanks, were within travelling distance, and had different shape settling tanks, i.e., rectangular, circular, etc.

Three plants were selected on the basis of the above criteria: (1) the Sarnia treatment plant which has long rectangular settling tanks, (2) the West Windsor treatment plant which has circular settling tanks, and (3) the WTC pilot plant which has a small circular settling tank. The added advantage of the pilot plant was that it could be run under relatively better controlled conditions of chemical treatment and overflow rate than the two full scale plants.

The functional and performance data for the three plants are as follows.

6.1 Sarnia Treatment Plant

The Sarnia Water Pollution Control Centre is a primary treatment plant treating on average about 8 MIGD (3.64×10^4 m^3/day) wastewater. The treatment consists of screening, pre-aeration, settling, chlorination, anaerobic sludge digestion and sludge disposal in lagoon. The treated effluent is discharged into the St. Clair River.

The plant is designed for 8 MIGD flow with four rectangular settling tanks, each having the following physical and hydraulic features:

Length	135 ft	(40.5 m)
Width	30 ft	(9.0 m)
Depth (average)	9 ft	(2.7 m)
Volume	36,500 ft^3	(1035 m^3)
Weir length	162 ft	(49.5 m)
Surface overflow rate	390 gpd/ft^2	(19 m^3/m^2/day)
Weir loading	12,300 gpd/ft	(185 m^3/m^2/day)
Outlet trough	3	
Length	22.5 ft	(6.8 m)
Width	2 ft	(0.6 m)
Detention time	2-3/4 hr	

The plan and elevation view of the settling tank is shown in Figure 1.

The plant performance data for the period from September 1971 to December 1972 were analyzed statistically using flow rate, suspended solids, BOD and total phosphorus as parameters. The summary of the results is given in Table 1 (for details, see Heinke, 1973).

6.2 Windsor Treatment Plant

The Windsor Treatment Plant is a primary treatment plant treating on average about 21 MIGD (9.5×10^4 m^3/day) wastewater. The treatment consists of degritting, screening, settling, chlorination, sludge dewatering and sanitary land filling. The treated effluent is discharged into the Detroit River.

The plant has four circular settling tanks each with the following physical and hydraulic features (see Figure 2):

Surface diameter	120 ft	(36 m)
Surface area	11,300 ft^2	(1020 m^2)
Side wall depth	11 ft	(3.3 m)
Volume	760,000 gal	(3450 m^3)
Weir length	375 ft	(107.1 m)
Surface overflow rate	532 gpd/ft^2	26.6 m^3/m^2/day)
Weir loading	16,800 gpd/ft	(250 m^3/m/day)
Detention time	3.1 hr	

The plant performance data for the years 1971 to 1972 have been summarized in Table 2. The data for chemical treatment could be obtained for only short periods of time. The City of Windsor experimented briefly with chemical treatment (alum and polymer Purifloc A23) from the 5th of May to the 16th of July, 1972. When chemical treatment started in January 1974 on a regular basis, the operation of the plant was frequently interrupted due to construction work for the new chemical treatment facilities. Due to the temporary nature of the chemical feeding system and lack of proper control of chemical dosages, most of the data recorded in 1974 were not reliable and, therefore, are not included in the performance analysis.

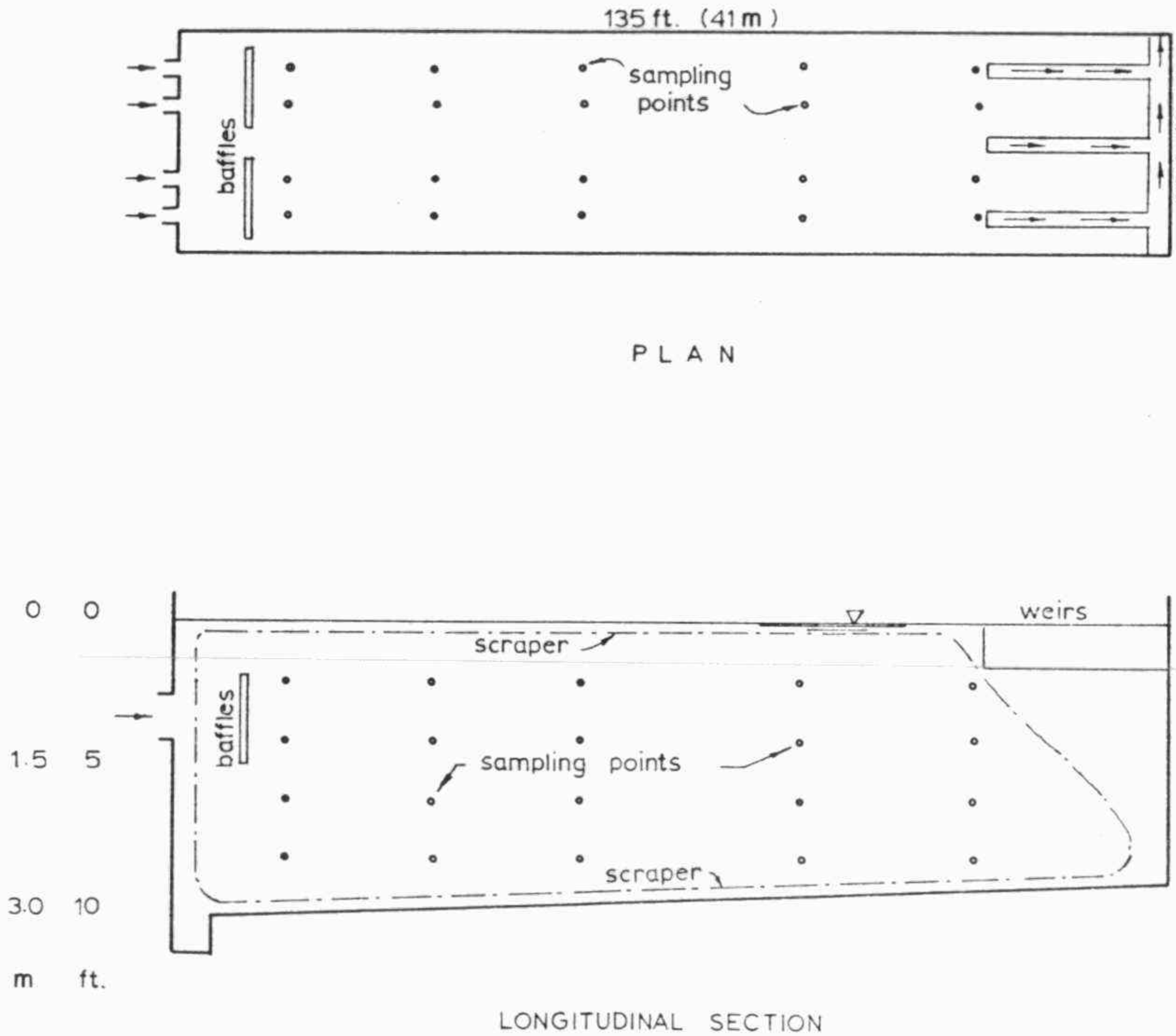


FIGURE 1. PLAN AND LONGITUDINAL SECTION OF SETTLING TANK AT SARNIA

TABLE 1. INFLUENT AND EFFLUENT CHARACTERISTICS OF WASTEWATER AT SARNIA, 1971 AND 1972

A. INFLUENT

Parameters	Average	Range Max.	Range Min.
Flow Rate, MGD	6.35	12.00	5.25
m^3/day	2.88×10^4	5.45×10^4	2.38×10^4
Overflow Rate, gpd/ft^2	390	2090	326
m^3/m^2/day	19	102	16
Suspended Solids (mg/l)	102	608	8
BOD (mg/l)	88	182	52
TOTAL P (mg/l)	5.73	22.6	2.18

B. EFFLUENT

Chemical Addition	Suspended Solids mg/l Avg.	Max.	Min.	BOD mg/l Avg.	Max.	Min.	Total Phosphorus mg/l Avg.	Max.	Min.
None	38	102	4	63	152	33	5.2	8.0	1.0
Ferric Chloride	23	74	9	34	80	17	0.9	5.3	0.2
Ferric Chloride plus A23	12	54	4	31	59	25	0.8	2.9	0.1
Alum	37	49	20	40	61	27	1.5	3.3	0.4
Alum plus A23	30	73	19	37	55	27	1.4	2.9	0.2

Chemical Dosages: Ferric Chloride* 10-20 mg/l, Alum** 80-100 mg/l, Polymer 0.3-0.5 mg/l.

* as Fe^{+++}
** as alum

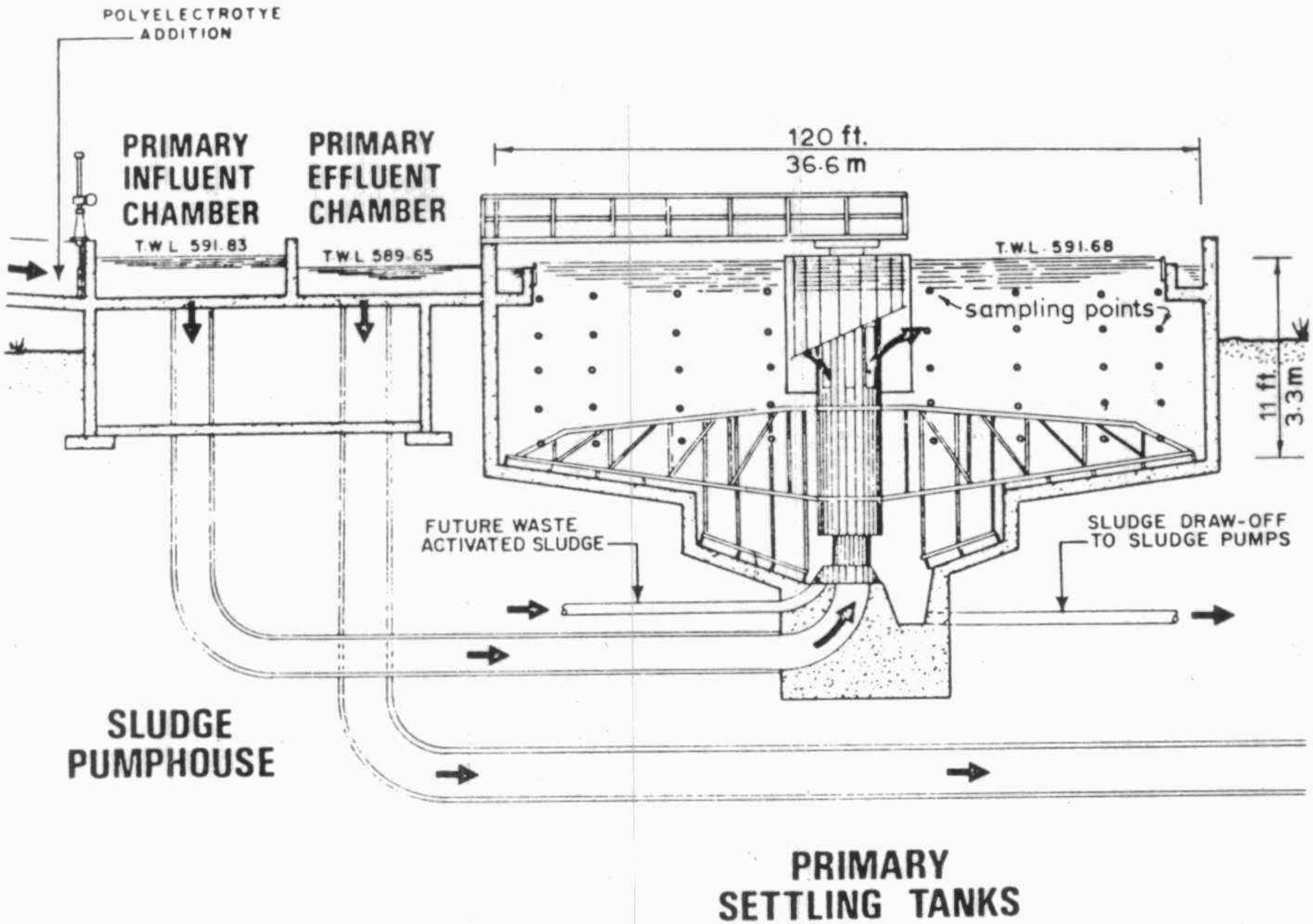


FIGURE 2. ELEVATION OF SETTLING TANK AT WINDSOR

TABLE 2. INFLUENT AND EFFLUENT CHARACTERISTICS OF WASTEWATER AT WINDSOR, 1971 AND 1972

A. INFLUENT

Parameters	Average	Range	
		Maximum	Minimum
Flow Rate, MGD	16.0	72.5	5.2
m^3/day	7.25×10^4	33.0×10^4	2.4×10^4
Overflow Rate, gpd/ft^2	350	1600	115
m^3/m^2/day	18	80	6
Suspended Solids (mg/l)	102	1054	26
BOD (mg/l)	101	346	27
TOTAL P (mg/l)	5.1	9.5	2.0

B. EFFLUENT

Chemical Addition	SS (mg/l)			BOD (mg/l)			Total P (mg/l)		
	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.
None (1971-1972)	61	309	22	76	297	21	4.8	9.3	1.9
Alum Only (5th-23rd May/72)	42	129	8	36	90	12	1.9	5.9	0.3
Alum plus Polymer (24th May-16th July/72)	30	60	6	36	77	14	1.1	2.6	0.3
Ferric Chloride plus Polymer (22nd Dec./74 - 11th Jan./75)	36	73	21	50	120	21	0.7	1.6	0.4

Chemical Dosages: Alum* 100 mg/l, Ferric Chloride** 17 mg/l, Polymer 0.3-0.4 mg/l.

* as Alum

** as Fe^{+++}

6.3 WTC Pilot Plant at Burlington

The WTC pilot plant at Burlington consists of a circular rapid mixing tank, a rectangular flocculation tank and a circular settling tank. The screened, degritted wastewater is pumped from the Burlington Skyway Treatment plant. The flow through the pilot plant can be varied to obtain various overflow rates. The inorganic chemical is added in the rapid mixing tank and the organic chemical is added at the inlet of the flocculation tank. Ferric chloride (at 18 mg/l as Fe^{+++}) and polymer (at 0.3 mg/l), as determined from the jar tests, were used in the study.

The circular settling tank has the following physical features (see Figure 3):

Diameter of tank	8 ft	(2.4 m)
Surface area	50 ft^2	(4.6 m^2)
Average depth	7 ft	(2.1 m)
Volume	2192 gal	(10.0 m^3)
Weir length	22 ft	(6.7 m)

The summary of the pilot plant performance analysis is given in Table 3.

6.4 Discussion

The detailed analysis and discussion of the Sarnia and Windsor plants' performances has been dealt with in the previously published report (Heinke, 1973) and in the unpublished report, May 1974.

A cursory look at Tables 1 and 2 shows that the Sarnia settling tanks were working very well and producing effluent low in suspended solids, BOD and phosphorus. On the other hand, the Windsor settling tanks were working inefficiently and producing effluent of inferior quality, particularly in comparison with the Sarnia tanks.

The influent to the pilot plant was much stronger than at the other two. On a percentage removal basis, the performance of the pilot settling tank happened to be somewhere in between Sarnia and Windsor.

Chemical addition (alum as well as ferric chloride) was very effective in removing suspended solids, BOD and total phosphorus. The addition of polymer in combination with ferric chloride or alum further improved the quality of effluent.

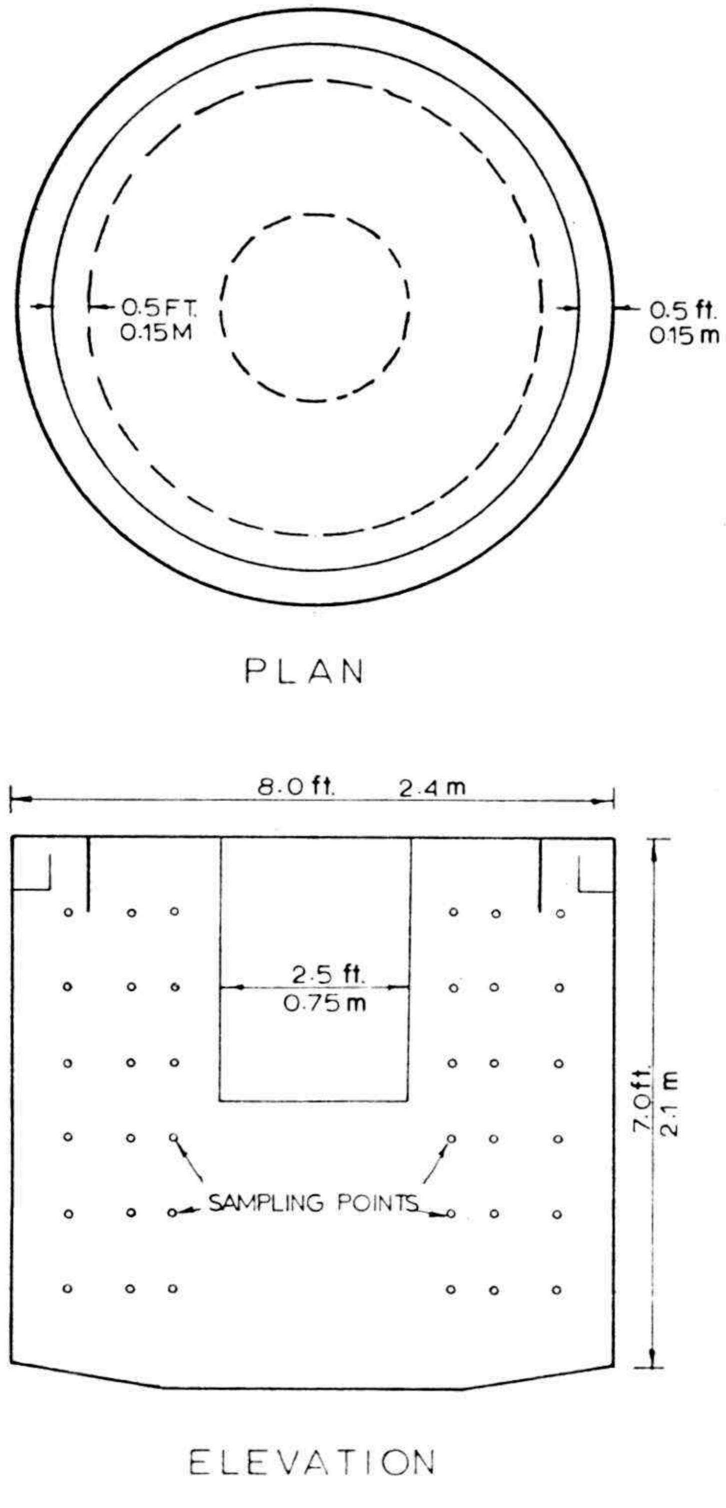


FIGURE 3. PLAN AND ELEVATION OF SETTLING TANK AT BURLINGTON

TABLE 3. INFLUENT AND EFFLUENT CHARACTERISTICS OF WASTEWATER AT WTC, BURLINGTON

A. INFLUENT

Parameters	Average	Range	
		Maximum	Mimimum
Suspended Solids (mg/l)	220	480	118
BOD (mg/l)	134	274	46
Total P (mg/l)	6.2	8.7	4.0

B. EFFLUENT

(Overflow rate 600 gpd/ft^2 or 30 m^3/m^2/day)

Chemical Addition	SS (mg/l)			Bod (mg/l)			Total P (mg/l)		
	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.
None	104	134	84	93	114	78	4.4	4.9	3.3
Ferric Chloride	55	72	26	49	56	41	1.2	1.7	0.4
Ferric Chloride plus Polymer	31	52	14	32	38	24	1.2	1.7	1.0

Chemical Dosages: Ferric Chloride* 18 mg/l, Polymer 0.3 mg/l.

* as Fe+++

Ferric chloride addition produced better effluent (in SS, BOD, P) than the alum addition. In Windsor, however, alum addition seemed to promote the removal of suspended solids and BOD more efficiently, but phosphorus removal was better with ferric chloride addition. It should also be noted that, in Windsor, alum was introduced at the raw sewage pump (which probably provided relatively better mixing conditions) whereas ferric chloride was added to the grit removing tank.

7. SETTLING CHARACTERISTICS OF FLOCS UNDER QUIESCENT CONDITIONS

When a suspension of particles or flocs enters a settling tank it is subjected to settling under the force of gravity, flocculated by eddy currents, mixed, diffused and dispersed by diffusion and dispersion forces in the tank, and finally forced to leave the settling tank much earlier than its allotted residence time due to density and short-circuiting currents. In this chapter the settling behaviour of physical-chemical flocs was determined in isolation from all the other influencing factors caused by flow in the settling tank. In the subsequent chapter, the hydraulic behaviour of settling tanks is analyzed, and its possible effects on settling performance studied.

To complete this phase of the study, about 139 settling column tests (in addition to 50 tests in Toronto) were performed at Sarnia, Windsor and Burlington under the following chemical conditions:

without chemical addition	(50 tests)
with Ferric Chloride addition	(20 tests)
with Alum addition	(12 tests)
with Ferric Chloride plus Polymer addition	(41 tests)
with Alum plus Polymer addition	(16 tests)

Of all the tests, 59 were peformed at Sarnia, 70 at Windsor and 10 at Burlington. Settling analyses showed that the settling behaviour of flocs at all three plants was quite similar and that the settling performance of alum and ferric flocs was very comparable. Consequently, the results of all the tests have been summarized into the following three categories:

(i) settling characteristics without chemical addition,
(ii) settling characteristics with Alum (or Ferric Chloride) addition,
(iii) settling characteristics with Alum (or Ferric Chloride) and Polymer (Dow-Purifloc A23) addition.

The settling characteristics of physical-chemical flocs were examined in relation to the following parameters:

- overflow rate,
- mixing,

- detention time,
- settling depth.

7.1 Results

The following figures were developed from settling column tests carried out under quiescent conditions.

Figure 4 shows the effect of overflow rate on clarification efficiency, with and without chemical addition after 30 and 60 minutes of settling time (no additional mixing applied).

Figure 5 shows the effect of additional mixing with ferric chloride (with and without polymer) addition. The effect of additional mixing was not studied without chemical addition, as it was assumed to be insignificant in this case.

Figure 6 (typical cases) shows the effect of settling time on clarification efficiency with depth of column as a parameter, with and without chemical addition (no additional mixing applied).

The parameter used in developing Figures 4 to 6 inclusive is the average of mean suspended solids in the settling column at various detention times (in percent of initial suspended solids in the suspension).

7.2 Discussion of Results

In this subsection, an attempt has been made to evaluate and show the effect of various parameters separately instead of relating their combined effects to clarification efficiency. For a real tank, design parameters such as overflow rate, detention time, surface area and depth of tank, etc., are interrelated and cannot be isolated from each other for study. The settling column analysis has, therefore, an added benefit in allowing this separation.

7.2.1 Effect of overflow rate

Figure 4 show the effect of overflow rate on clarification efficiency for domestic sewage (as % SS remaining), with and without chemical addition, under quiescent conditions. It shows that, for a given detention (settling) time, overflow rate has a small effect on the clarification of flocculent suspensions. From settling column tests, it is estimated that if the overflow rate increases from 500 to 2000 gpd/ft^2 (or 25 to 100

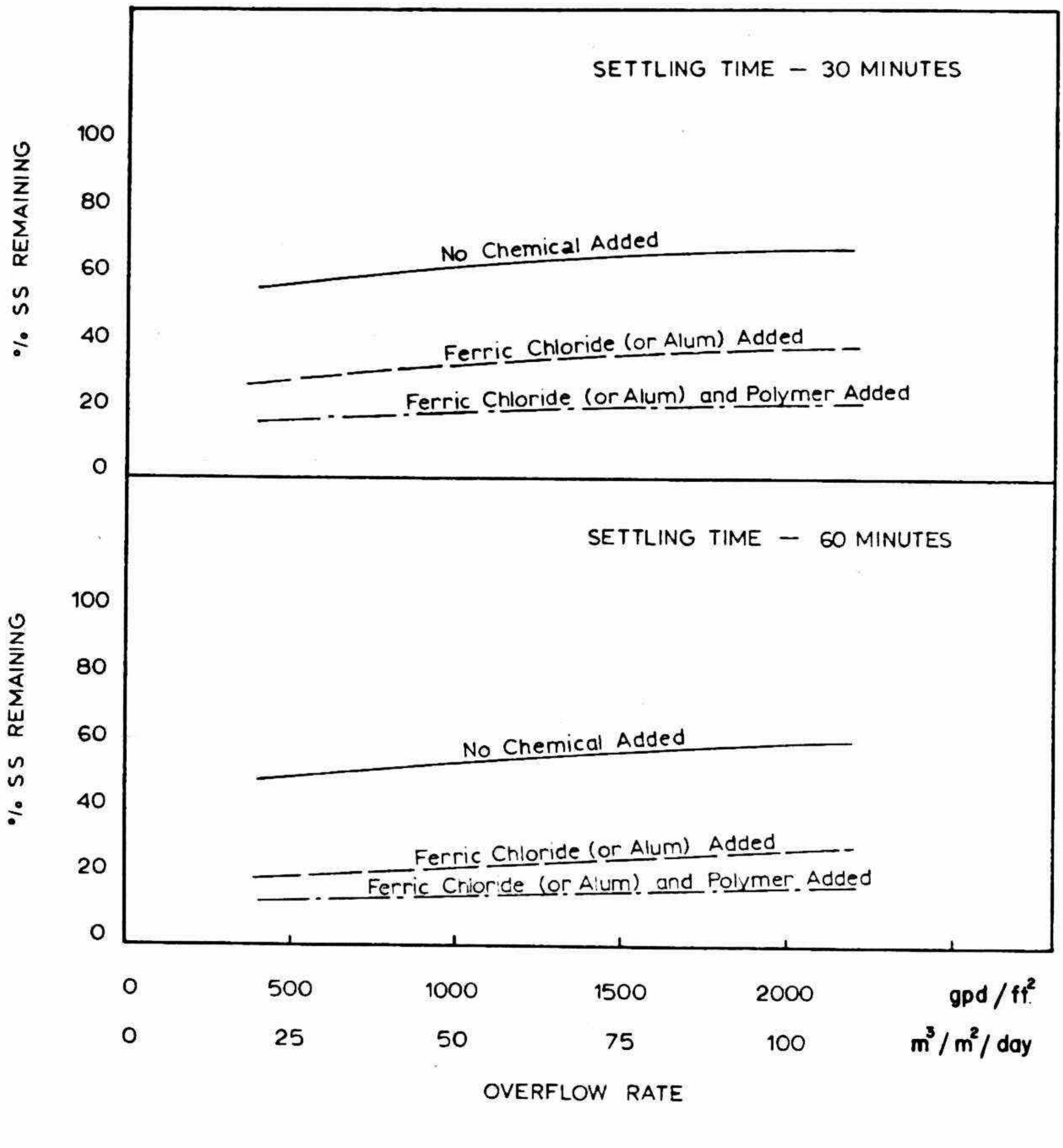


FIGURE 4. EFFECT OF OVERFLOW RATE ON CLARIFICATION EFFICIENCY

m^3/m^2/day) the suspended solids in the effluent will increase by about 10% without chemical addition, 9% with ferric chloride or alum addition, and 5% with ferric chloride or alum and polymer additions. Percentages stated refer to initial suspended solids concentration.

7.2.2 Effect of mixing

In Sarnia and Windsor, chemicals were added at a location where reasonable mixing conditions existed (in a pre-aeration tank at Sarnia, and a grit removal tank or at a raw sewage pump at Windsor) but which provided only a few minutes of mixing/flocculation time particularly after the polymer was added and before the suspension was discharged into the settling tank. The samples for the settling column tests were taken just before the inlet to the tank and poured into the settling column initially without any further mixing.

The settling performance predicted by the settling column compared very closely with that of the settling tank at low overflow rates (about 500 gpd/ft^2 or 25 m^3/m^2/day, when a scale-up factor of 2 was applied to detention time as commonly practiced (Eckenfelder and Ford, 1970). At higher overflow rates, however, the settling tank produced much better effluent quality than predicted by the settling column. From this lack of comparison at higher overflow rates it was believed that the suspensions taken for settling tests were not fully flocculated, that further mixing/flocculation was occurring in the tank, and that the flocs would grow when subjected for further mixing before the settling column test. Therefore a series of tests was conducted in which suspensions with chemical addition were slowly mixed for 20 minutes by a propeller-type mixer before settling in the column. This series of tests showed significant improvement in settling rate due to additional mixing (see Figure 5 curves A and B). These tests were carried out in Windsor only but, probably, the general findings are applicable to Sarnia as well.

Figure 5 (curves A and B) shows that the settling rate of mechanically flocculated suspensions was much faster than that of the unstirred suspensions. It should be noted that this difference diminishes with increase in detention time. The extent of improvement in settleability will depend heavily on the degree of flocculating potential existing

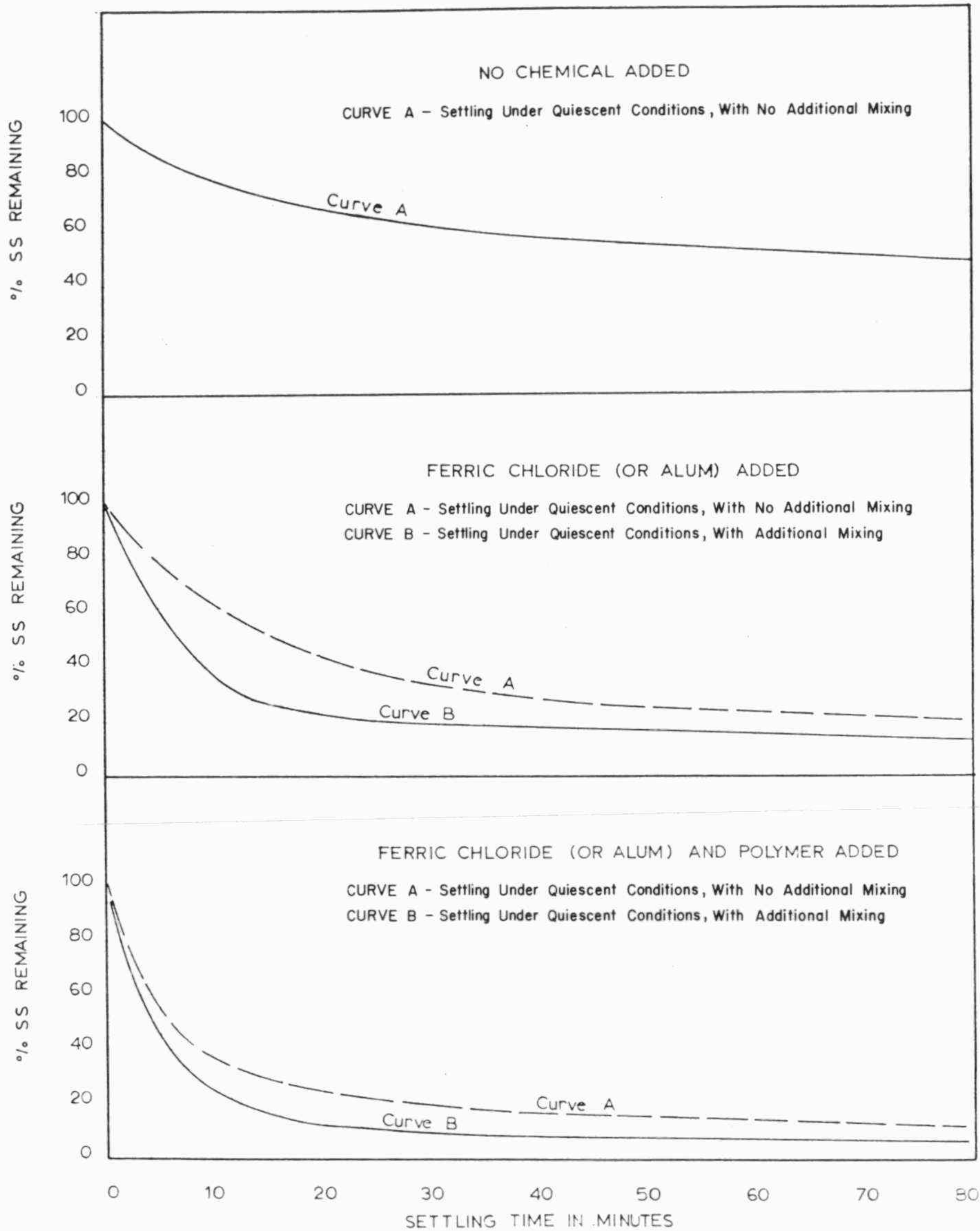


FIGURE 5. EFFECT OF TURBULENCE/FLOCCULATION ON CLARIFICATION EFFICIENCY

in the suspension. If the flocs are already fully developed, slow mixing may not have any beneficial effect and curves A and B in Figure 5 will tend to coincide. On the other hand, if the suspension is mixed prior to the settling tank for a short time only, then slow mixing will be beneficial to floc formation and subsequent faster settling. Further work in this area is planned.

7.2.3 Effect of detention time

Figure 5 also shows the effect of detention time, with partial flocculation (curve A) and with complete flocculation (curve B). The curves are fairly steep in the initial range of detention time, and become progressively flatter with the passage of time. When flocs were fully developed most of the settling occurred in about 45 minutes without chemical addition, and in about 20 minutes with chemical addition (curve B). When flocs were not fully developed (curve A) clarification required a little longer (45 minutes for ferric chloride or alum only, and about 30 minutes in combination with polymer).

If detention time is increased beyond what is described above, only a small improvement in effluent quality will be achieved, as evident from the flat curve. On the other hand, if the detention time is reduced much below the stated times, drastic deterioration of effluent quality will result. It is, therefore, very important that, for effective performance of settling tanks, all of the wastewater flow should be receiving the appropriate minimum detention times indicated.

7.2.4 Effect of settling depth

Figure 6 shows the effect of settling time on clarification efficiency, with and without chemical addition, with settling depth as a parameter. The curves represent the average over the depth shown. For a given detention time, clarification deteriorates only slightly as settling depth increases. The effect of depth further diminishes with an increase in detention time, particularly with chemical addition. With ferric chloride or alum and polymer additions, depth of settling ceases to have any significant effect on settling efficiency after about 30 minutes of detention time. This may mean that only small improvement in clarification efficiency can be expected from the use of trays or tubes, when chemicals are used.

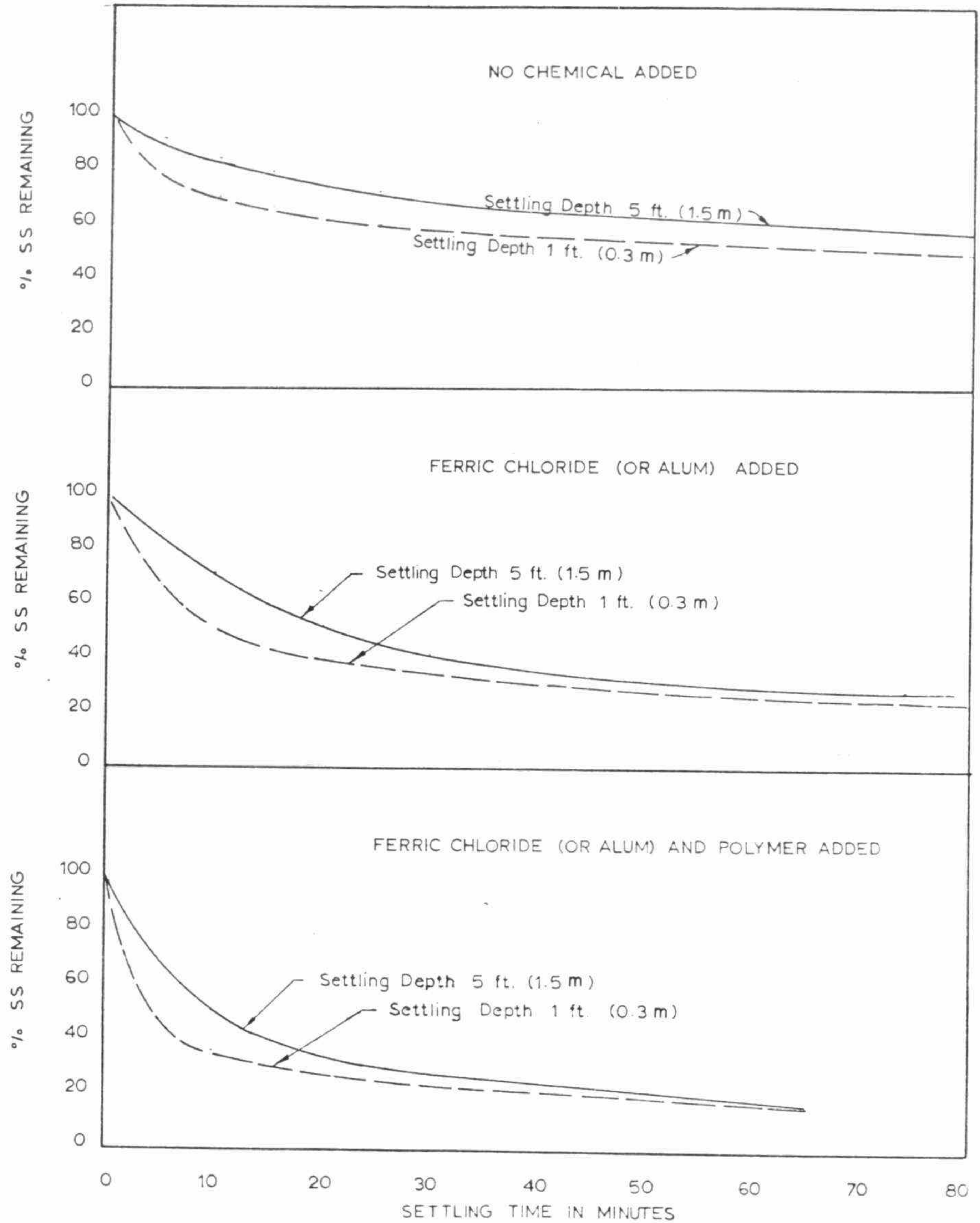


FIGURE 6. EFFECT OF SETTLING DEPTH ON CLARIFICATION EFFICIENCY

In summary, laboratory studies of settling tests on domestic sewage, with and without chemical addition, have shown that the most important parameter for efficient settling is effective detention time. The influence of either overflow rate or settling depth alone is minor. Chemical addition greatly increases clarification. Comparison of results on effluent quality predicted from laboratory settling tests, applying accepted scale-up factors, and actual plant performance is good. Mixing of suspensions prior to settling is beneficial to faster settling.

7.3 Development of Settling Performance Curves (S-Curves)

It has been discussed earlier in this section that gentle mixing of suspension will improve floc formation and, therefore, clarification rate of suspension. When the suspensions with chemical addition are disharged into the settling tank, they are subjected to mixing conditions. As the flow proceeds through the tank, the settling rate of flocs improves progressively in response to the improvement and development of flocs in flocculating mixing condition until the flocs are fully developed. Assuming that the flocculation in the tank is completed in about 20-40 minutes, depending on the intensity of turbulence (faster flocculation under higher mixing conditions), a curve (labelled as S-curve in Figure 7) was drawn starting tangentially from the curve A at zero detention time and meeting the curve B tangentially in about 20-40 minutes time. This curve is believed to represent the settling rate of flocs under actual mixing conditions.

The S-curves so developed can be expressed in the following general form:

$$S_o - S = \frac{k' \, St^n}{F^r} \qquad (1)$$

or

$$S = \frac{S_o F^r}{K' \, t^n + F^r} \qquad (2)$$

where:

S_o = suspended solids in influent to the settling tank, mg/l,

S = suspended solids in effluent, mg/l,

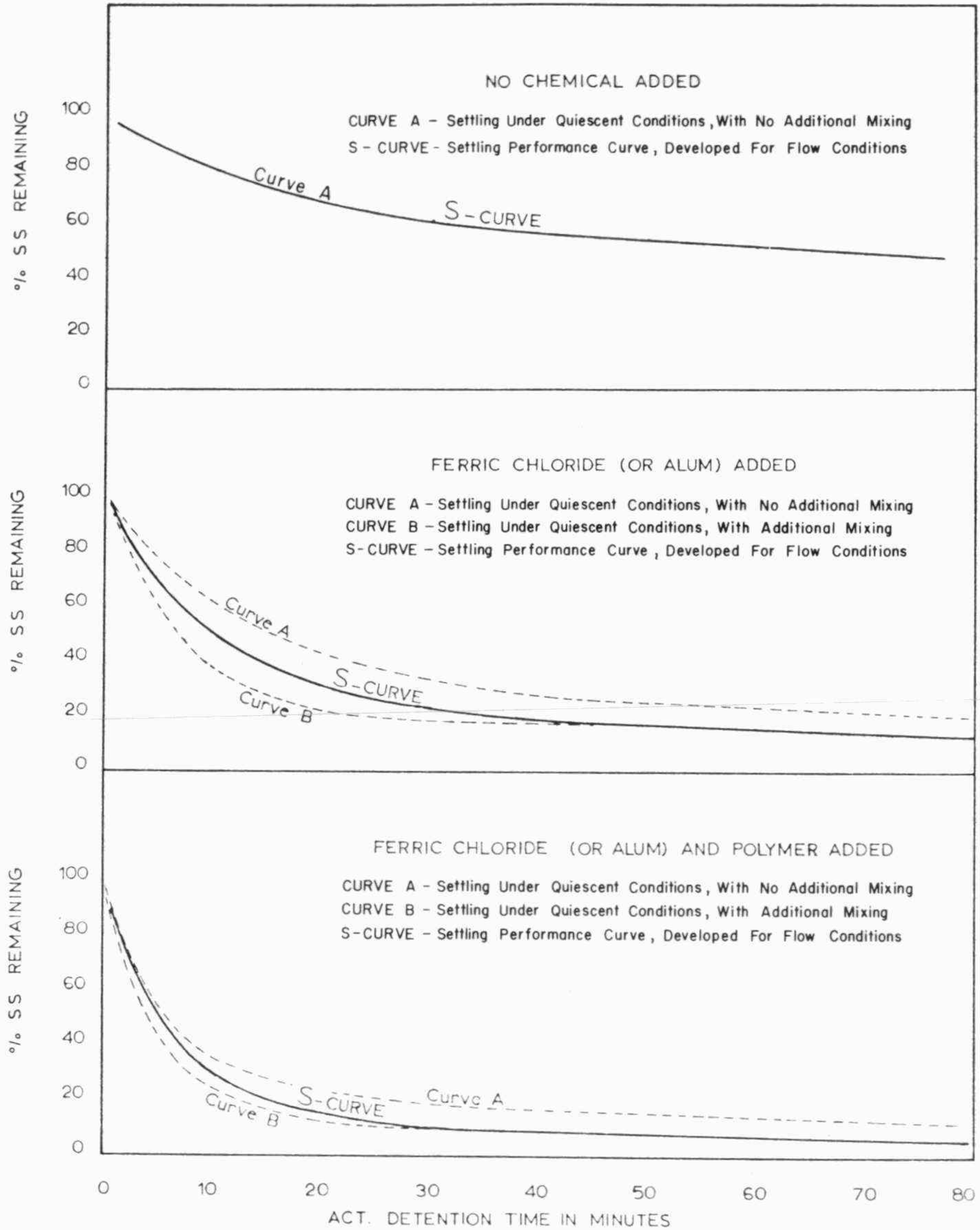


FIGURE 7. SETTLING PERFORMANCE CURVES (S-CURVES)

t = settling or detention time in minutes,

F = overflow rate,

k' = flocculation constant,

n = settling constant,

r = constant.

Within the range of the study, the effect of overflow rate was very small, particularly with chemical addition. Therefore, the effect of overflow rate was ignored in the final form of the model. By replacing the factor k'/F^r by another constant k, the above equations can be rewritten as follows:

$$S_o - S = k\, S t^n \tag{3}$$

or

$$S = \frac{S_o A}{t^n + A} \tag{4}$$

where:

$A = 1/k.$

Equation 3 shows that suspended solids removal at any time, t, is proportional to suspended solids remaining, and t^n. The constant k gives the rate of flocculation of suspension under flocculating conditions. The values of constants for the suspensions under study were worked out as follows:

Chemical Addition	n	k	A = 1/k
No Chemical	0.64	0.067	15.0
Ferric Chloride (or Alum)	0.90	0.133	7.5
Ferric Chloride (or Alum) plus Polymer A23	0.93	0.286	3.5

The values of k and n show that the rates of flocculation and settling increased with the addition of chemicals, and were highest with ferric chloride (or alum) plus polymer addition.

It should be noted that this model has been developed from a 6 ft (1.8 m) deep column, but is thought to be applicable to deeper or shallower tanks equally well, particularly with chemical addition, because in this case, settling depth does not play a significant role in the removal of suspended solids.

With the length of column used in the study (6 ft or 1.8 m), and the operational limitations of the plants, it was not possible to estimate or study the effects of overflow rates with reasonable confidence in the ranges far above 2000 gpd/ft^2 (100 m^3/m^2/day). However, the trend of curves shown in Figure 4 indicates that settling tanks might be operated effectively at overflow rates considerably above 2000 gpd/ft^2 (100 m^3/m^2/day), as long as sufficient settling time (as discussed in other sections of the report) is allowed. There will be some deterioration of effluent, as is indicated by the curves in Figure 4. Past experience indicates that at very high overflow rates, wash-out will occur. Further studies are needed to determine the critical range of overflow rate.

It is, however, believed that the results of this study can be projected to overflow rates up to about 2000, 3000, and 4000 gpd/ft^2 (100, 150, and 200 m^3/m^2/day) without chemical, with ferric chloride (or alum) and with ferric chloride (or alum) plus polymer addition, respectively. This projection of results should be checked out on plant-scale basis before these figures are used in the design criteria.

It should be noted that all the comments made here apply to domestic wastewaters of similar composition to those used in the study.

8 HYDRAULIC BEHAVIOUR OF SETTLING TANKS

The purpose of this phase of the program was to study the pattern of flow in the rectangular and circular tanks with particular reference to the actual or effective detention time in the tank. Tracer studies were used to study the hydraulic behaviour of settling tanks. This technique is simple and proved very effective in translating a number of complicated hydraulic phenomena into a simple dimensionless curve (dispersion curve or C-curve). A number of valuable hydraulic efficiency parameters were developed from the analysis of this C-curve.

Ninety-seven dye tests were performed, at Sarnia (50 tests), Windsor (26 tests) and at Burlington (21 tests). In most tests, dye concentrations were measured at the effluent channel in order to develop the dispersion curve at various overflow rates. Some tests were carried out to measure the concentrations in the settling tank at various depths and locations to trace the flow paths and location of suspected dead zones. The latter part of the study was carried out in the circular tank in Windsor which showed signs of inefficient hydraulic behaviour and poor settling performance.

8.1 Results

Figure 8 shows a typical C-curve for the rectangular tank in Sarnia.

Figures 9 and 10 show a typical C-curve for the circular tanks at Windsor and Burlington, respectively.

Figure 11 shows a typical case of short-circuiting and density current (or presence of dead zones) in Windsor.

Figure 12 is a typical case to show the presence of eddy currents in Windsor.

Table 4 gives hydraulic efficiency parameters for settling tanks at Sarnia, Windsor and Burlington, for various overflow rates where:

- C_o - dose of tracer per unit volume of settling tank,
- C - tracer concentration in the effluent at time 't',
- t_i - time interval for initial indication of the tracer in the tracer in the effluent, in minutes,

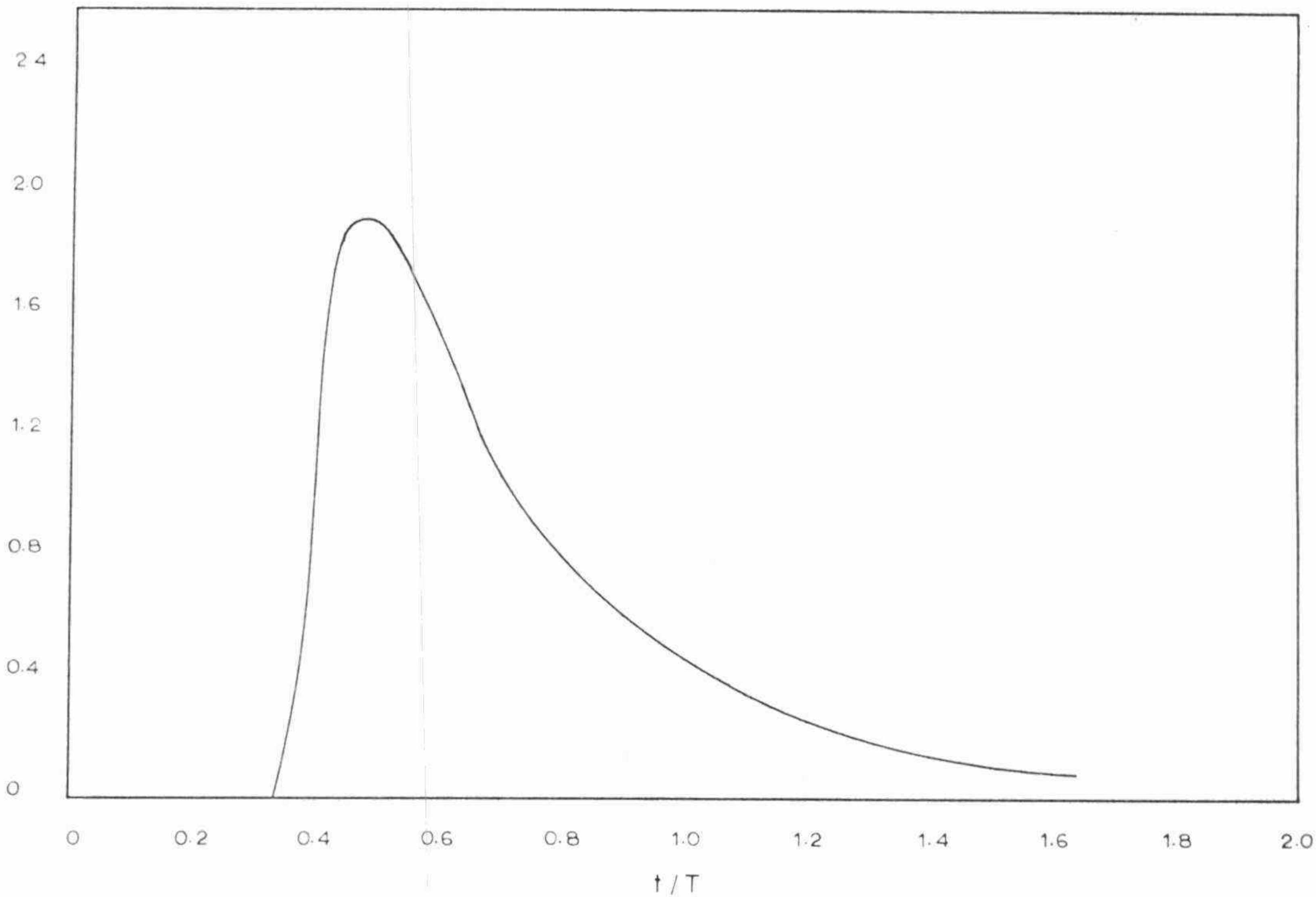


FIGURE 8. TYPICAL C-CURVE AT SARNIA

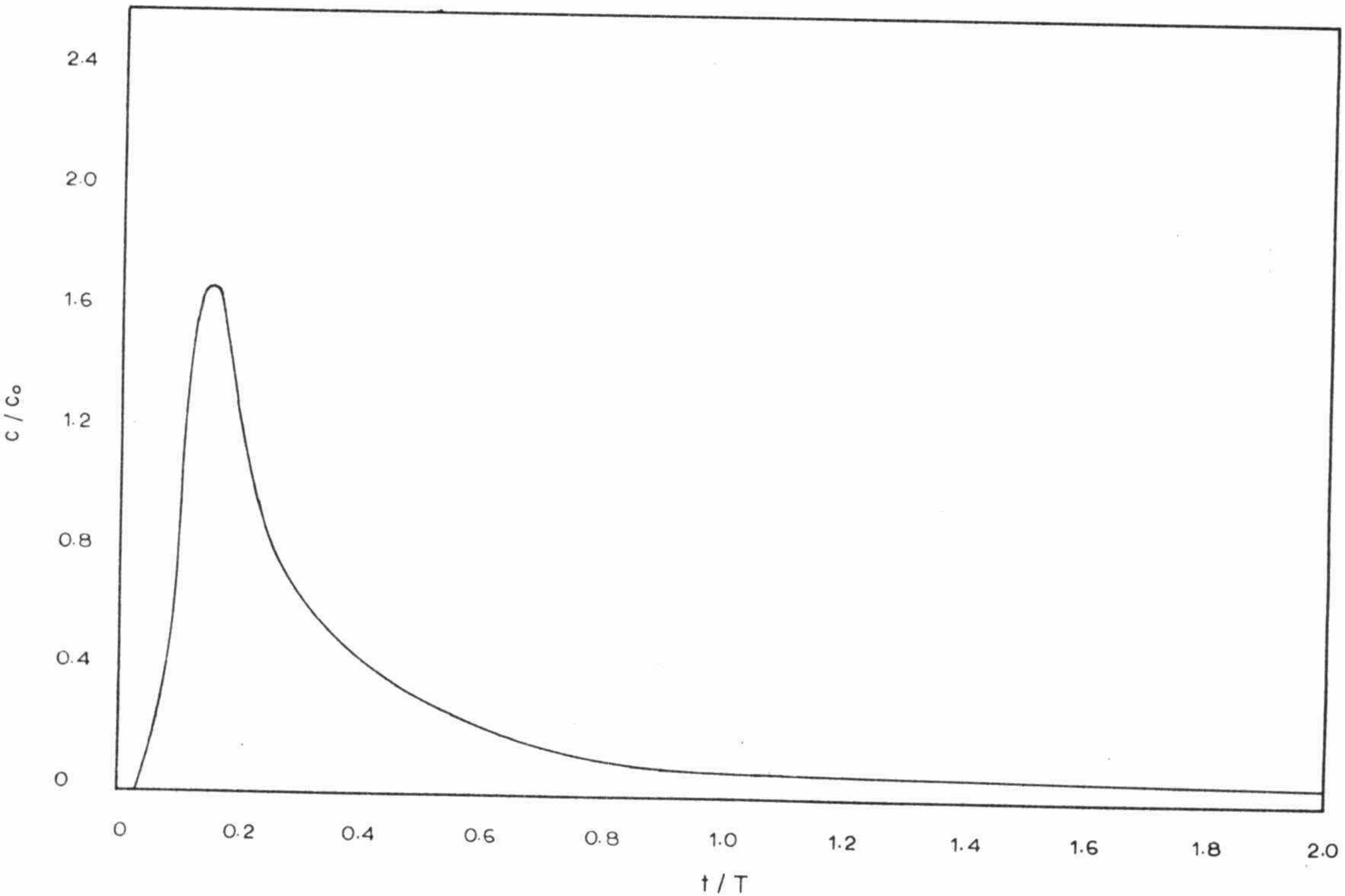


FIGURE 9. TYPICAL C-CURVE AT WINDSOR

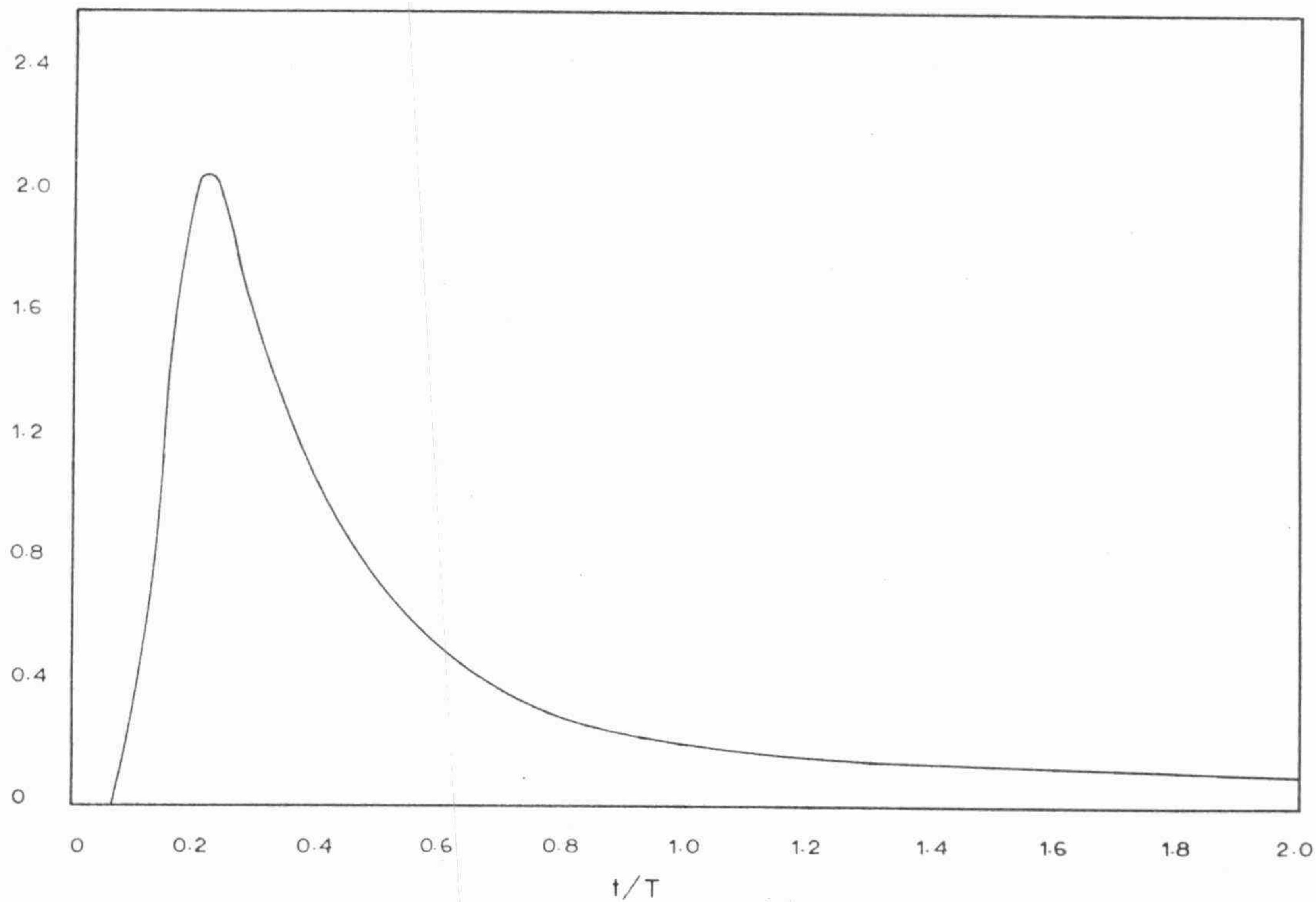


FIGURE 10. TYPICAL C-CURVE AT BURLINGTON

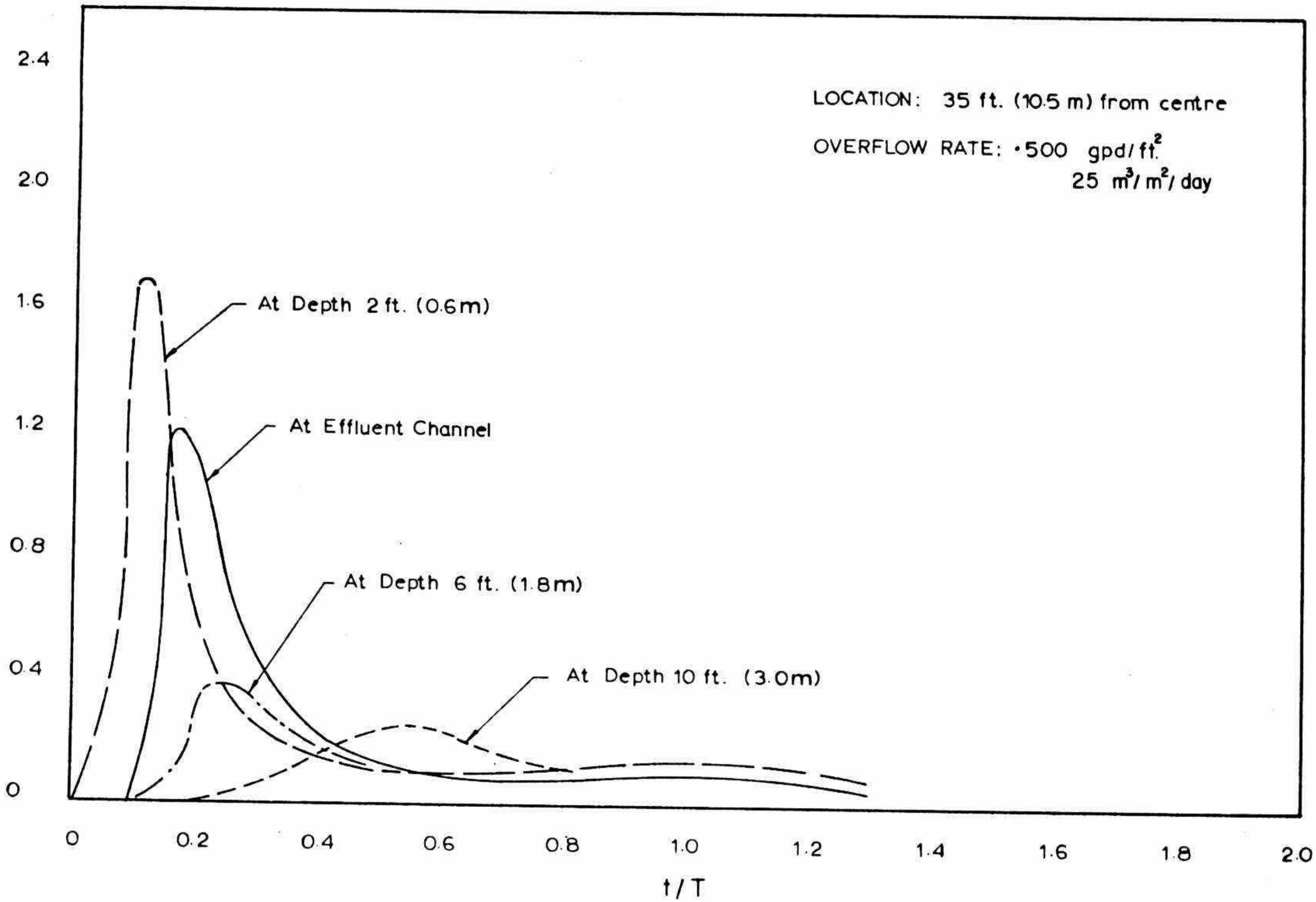


FIGURE 11. TYPICAL DISTRIBUTION OF DYE CONCENTRATION IN CIRCULAR TANK IN WINDSOR

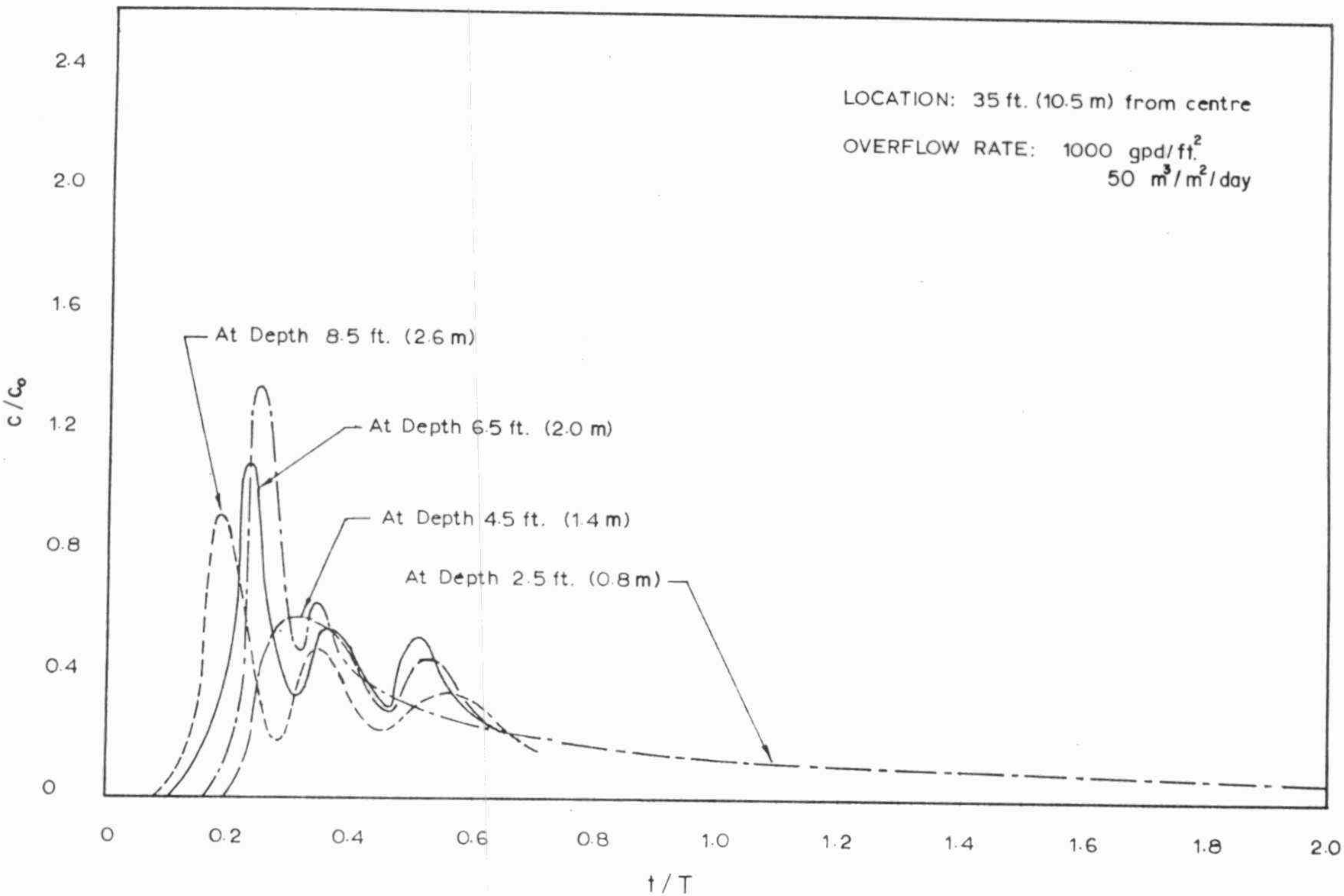


FIGURE 12. TYPICAL OSCILLATING DYE-CONCENTRATION CURVES IN CIRCULAR TANK IN WINDSOR

tp - time to reach peak or maximum concentration, in minutes,

tg - time to reach centroid of the curve (actual mean detention time), in minutes,

T - theoretical detention time, in minutes.

Table 5 gives indices of minimum and mean (actual) detention time.

Table 6 gives short-circuiting and dispersion indices for the rectangular tank at Sarnia and the circular tanks at Windsor and Burlington for various overflow rates.

Table 7 shows relative distribution of flow in the circular tank at Windsor at various hydraulic loadings.

8.2 Discussions of Results

8.2.1 Actual detention time and other hydraulic parameters

As defined earlier, actual mean detention time of flow is determined by the value of tg (centroid of C-curve). In the settling tanks, actual detention time is generally a lot shorter than the theoretical detention time due to short-circuiting and the presence of dead zones. In order to determine more realistic relationships between the settling column and tank performance efficiency, the study of this and other hydraulic parameters became necessary.

If, in a settling tank, flow is stable and there are no dead spaces or zones, the value of tg/t will be unity. But, if there are dead zones in the tank, in which there is little liquid displacement, the effective tank volume is less than the true volume and the value of tg/t, in this case, will be less than unity. The lower the value of tg/t, the worse the performance of the tank will be.

The results in Tables 4 and 5 show that the rectangular tank at Sarnia is much closer to ideal (average tg/T = 0.73) than the circular tank in Windsor (average tg/T = 0.36). This means that in the rectangular tank about 3/4 of the total volume is effective, whereas in the circular tank only 1/3 of the volume is effective. The results further show that the tg/t ratio increases, although to a small extent, with an increase in the overflow rate. For the pilot circular tank at Burlington,

TABLE 4. HYDRAULIC EFFICIENCY PARAMETERS

A. AT SARNIA

Overflow Rate		Parameters in Minutes				$\frac{\text{Act. D.T.}}{\text{Theor.D.T.}} \times 100$
gpd/ft^2	m^3/m^2/day	ti	tp	tg	T	
500	75	38*	60*	105*	160*	65.6%*
1000	50	24	39	62	80	77.5%
1500	75	19	31	41	53	77.4%
2000	100	16	25	29	40	72.5%

B. AT WINDSOR

Overflow Rate		Parameters in minutes				$\frac{\text{Act. D.T.}}{\text{Theor.D.T.}} \times 100$
gpd/ft^2	m^3/m^2/day	ti	tp	tg	T	
500	25	20	46	60	200	30.0%
1000	50	10	25	33	100	33.0%
1500	75	7	18	27	67	40.3%
2000	100	5*	15*	21*	50*	42.0*

C. AT BURLINGTON

Overflow Rate		Parameters in minutes				$\frac{\text{Act. D.T.}}{\text{Theor.D.T.}} \times 100$
gpd/ft^2	m^3/m^2/day	ti	tp	tg	T	
600	30	8	28	42	110	38.2%
1000	50	5	25	36	66	54.5%
1500	75	--	--	--	--	--
2000	100	5	16	24	33	72.7%

* Obtained by extrapolation

TABLE 5. INDICES OF MINIMUM (ti/T), AND ACTUAL MEAN (tg/T) DETENTION TIME

Overflow rate		Sarnia		Windsor		Burlington	
gpd/ft^2	m^3/m^2/day	ti/T	tg/T	ti/T	tg/T	ti/T	tg/T
500	25	0.24	0.66	0.10	0.30	0.07	0.38
1000	50	0.30	0.78	0.10	0.33	0.08	0.55
1500	75	0.36	0.77	0.10	0.40	--	--
2000	100	0.40	0.73	0.10	0.42	0.15	0.73

however, the value of tg/T varied over a great range (0.38 to 0.73) as the overflow rate increased from 600 to 2000 gpd/ft^2 (from 30 to 100 m^3/m^2/day).

Similarly, the comparison of other parameters between the Sarnia and Windsor plants shows that the dye front (ti) and peak (tp) appeared much earlier at Windsor than Sarnia. The value of ti/T, for example is higher (0.24 - 0.40) for the Sarnia tank than for Windsor (0.1). The hydraulic characteristics of the Burlington tank fall in between those at Sarnia and Windsor.

8.2.2 Short-circuiting and dispersion indices

The index of short-circuiting, as suggested by Murphy (1963) is calculated as follows:

$$\text{I.S.C.} = \frac{tg - tp}{tg}$$

The index of short-circuiting should be zero for an ideal basin (plug flow) and 1.0 for a perfect mixing basins with infinite short-circuiting.

Thirumurthi introduced the dispersion index to indicate the efficiency of a sedimentation tank (Thirumurthi 1969, and Levenspiel 1962). The dispersion index is calculated from variance of the C-curve (with actual dimensions) which is as follows:

$$\sigma_t^2 = \left(\frac{\Sigma t^2 c}{\Sigma c}\right) - \left(\frac{\Sigma tc}{\Sigma c}\right)^2$$

$$\sigma^2 = \frac{\sigma_t^2}{tg^2}$$

$$\sigma^2 = 2D + 3d$$

c = concentration at time t,

σ_t^2 = variance of C-curve in "time squared" units,

σ^2 = variance of C-curve (dimensionless),

d = dispersion index.

Thirumurthi stated that a tank with a lower dispersion index (deviates to a lesser degree from the ideal) is more efficient in sedimentation than a tank with a large dispersion index.

The dispersion and short-circuiting indices are applicable to those settling tanks in which most of the volume of the tank is effective and there are virtually no dead areas. In all the three tanks studied, there were fair to large amounts of dead areas present. Therefore, these indices did not give any meaningful conclusions for the settling tanks at Sarnia, Windsor or Burlington. The values of indices were, however, calculated for various overflow rates and recorded in Table 6.

The ti/T and tg/T indices produced more consistent and meaningful results at various overflow rates, particularly in relation to the performance of settling tanks. This has been further discussed in Section 10.

8.2.3 Flow pattern in circular tank

The analysis of C-curves indicated the presence of acute short-circuiting and dead zones in the circular tank in Windsor. To investigate this further, the pattern of flow was studied by tracing the dye concentrations at various depths and locations in the tank. The relative concentration and amount of dye detected (over a sufficiently long period of time) from various depths at a given location was assumed to be indicative of the relative intensity and amount of flow passing through various depths at that location. The results of this series of tests show that at Windsor:

a) When the plant was running on four tanks (overflow rate about 500 gpd/ft^2 or 25 m^3/m^2/day), the flow generally floated through the top layers of the tank leaving the bottom half of the tank ineffective. In some cases the flow pattern was reversed, and the flow went to the bottom and flowed along the bottom of the tank leaving the top half ineffective (see Figure 11 and Table 7).

b) When the plant ran on two tanks (overflow rate about 1000 gpd/ft^2 or 50 m^3/m^2/day), the flow became more uniformly distributed over the depth until about mid-radius of the tank (35 ft or 10.7 m from the centre) and, beyond that point, the flow stream became segregated and floated to the top (see Table 7).

TABLE 6. INDICES OF SHORT-CIRCUITING AND DISPERSION

Overflow Rate		Sarnia		Windsor		Burlington	
gpd/ft^2	$m^3/m^2/day$	Dispersion Index	Short-Circuiting Index	Dispersion Index	Short-Circuiting Index	Dispersion Index	Short-Circuiting Index
500	25	0.41	0.42	0.10	0.21	0.29	0.61
1000	50	0.42	0.33	0.12	0.21	0.12	0.35
1500	75	0.42	0.24	0.18	0.35	--	--
2000	100	0.46	0.15	--	--	0.11	0.27

NOTE: Because of the limited hydraulic capacity of effluent channel around the settling tank, Windsor settling tank could not be run at overflow rates greater than 1500 gpd/sq ft (75 $m^3/m^2/day$).

TABLE 7. DISTRIBUTION OF FLOW IN CIRCULAR TANK AT WINDSOR
(in percent of average flow)

Location from the Centre of Tank	20 ft (6.1 m)				35 ft (10.7 m)				50 ft (15.2 m)			
Depth	2.5 ft 0.8 m	4.5 ft 1.4 m	6.5 ft 2.0 m	8.5 ft 2.6 m	2.5 ft 0.8 m	4.5 ft 1.4 m	6.5 ft 2.0 m	8.5 ft 2.6 m	2.5 ft 0.8 m	4.5 ft 1.4 m	6.5ft 2.0 m	8.5 ft 2.6 m
Four tanks in operation	42	24	18	16	41	25	17	17	49	32	11	8
	15	21	28	36					37	27	19	17
Two tanks in operation					25	22	26	27	34	27	21	18
					26	23	26	25	20	25	26	29
					24	26	26	24				
One tank in operation					20	29	25	26	23	23	28	26

c) Under one tank operation (overflow rate above 2000 gpd/ft^2 or 100 m^3/m^2/day) the flow became more or less uniformly distributed over the depth throughout the settling tank (see Table 7).

From the results mentioned it appears that as the flow increases, the flow through the tank becomes more and more uniformly distributed (approaching the ideal condition). This may not be entirely true. The increase in flow rates does improve the hydraulic performance of the settling tank, but only to a small extent, as is indicated by the index tg/T. As the overflow rate increased from 500 to 2000 gpd/ft^2 (25 to 100 m^3/m^2/day) the value of tg/T increased from 0.30 to 0.42. In the case of the Burlington pilot plant, however, the value of tg/T increased from 0.38 to 0.73. The reason for such a difference may be the fact that the two circular tanks were hydraulically different (the diameter/depth ratio for the Burlington tank is one, whereas for the Windsor tank it is more than ten).

The C-curves developed for various depths in the circular settling tank at Windsor show a number of peaks of successively reducing intensity (see Figure 12). This generally happened at medium to high overflow rates (1000-2000 gpd/ft^2 or 50-100 m^3/m^2/day) and may be an indication of the presence of large eddy currents or rollers (a mass of water rotating in vertical plane) in which there is only a little displacement of water. The dye, probably, was caught in these rollers and moved in a circle from top to bottom and bottom to top, which resulted in oscillating curves on the graph. The dye was slowly released from this mass of water which is indicated by the reducing intensity of successive peaks of curves and later a long lasting tail. The C-curve for the effluent point, however, always showed one peak but with a long tail.

In Sarnia no such tests were performed, but it was expected that the flow in the rectangular tank in Sarnia was stable and fairly uniform with only small 'dead' regions of flow, as would seem to be indicated by various hydraulic parameters.

To summarize this discussion, it can be stated that the rectangular tanks in Sarnia are closer to the ideal settling basin and much superior to the circular tanks at Windsor. The circular tanks in Windsor suffer drastically from the presence of dead zones and short-circuiting, and have a very unstable flow pattern.

The short-circuiting and dispersion indices were not applicable to the tanks under study because of the presence of dead zones in the tanks. Other hydraulic parameters, such as ti, tp, and tg are useful parameters for expressing hydraulic and performance efficiencies of settling tanks. The tg/T index measures the relatively effective settling volume of a tank and ti/T the minimum flow-through time. The greater the values of tg/T and ti/T (maximum 1.0) the better will be the hydraulic behaviour of the settling tank.

9. SETTLING OF PHYSICAL-CHEMICAL FLOCS IN REAL TANKS

This phase of the research work was carried out to investigate the settling behaviour of physical-chemical flocs in the real tank, particularly in relation to flow pattern and intensity of turbulence, at various overflow rates, and with and without chemical addition. In this study, ferric chloride alone, and in combination with polymer (Dow-Purifloc A23), was used for the chemical treatment of wastewater.

To carry out this study, suspended solids and velocity measurements were taken at various depths and locations to develop suspended solids and velocity profiles at various overflow rates, and with and without chemical addition (for detail and procedure, see Section 5).

One hundred and eighteen tests were performed, at Sarnia (33 tests), Windsor (45 tests) and Burlington (40 tests), and the results are presented as follows.

9.1 Results

Figure 13 shows the velocity profiles in the settling tank when the plant was operated on three, two, and one tank, at Sarnia. The velocity profiles were not affected by chemical addition and, therefore, the results for various chemical conditions were lumped together.

Figures 14, 15 and 16 show suspended solids profiles in the Sarnia settling tank when the plant was operated on three, two and one tank, with and without chemical addition.

Figure 17 shows the velocity profiles at various overflow rates at Windsor.

Figures 18, 19 and 20 show the suspended solids profiles for various overflow rates with and without chemical addition at Windsor.

Figure 21 shows the velocity profiles at various overflow rates at Burlington.

Figures 22, 23 and 24 show the suspended solids profiles for various overflow rates with and without chemical addition at Burlington.

It should be noted that the elevations of settling tanks shown in the figures for Sarnia and Windsor are not in true proportion but distorted in horizontal dimension. The profiles, therefore, look steeper than they really are. In the case of Burlington, the tank was elongated horizontally and, therefore, the profiles look flatter.

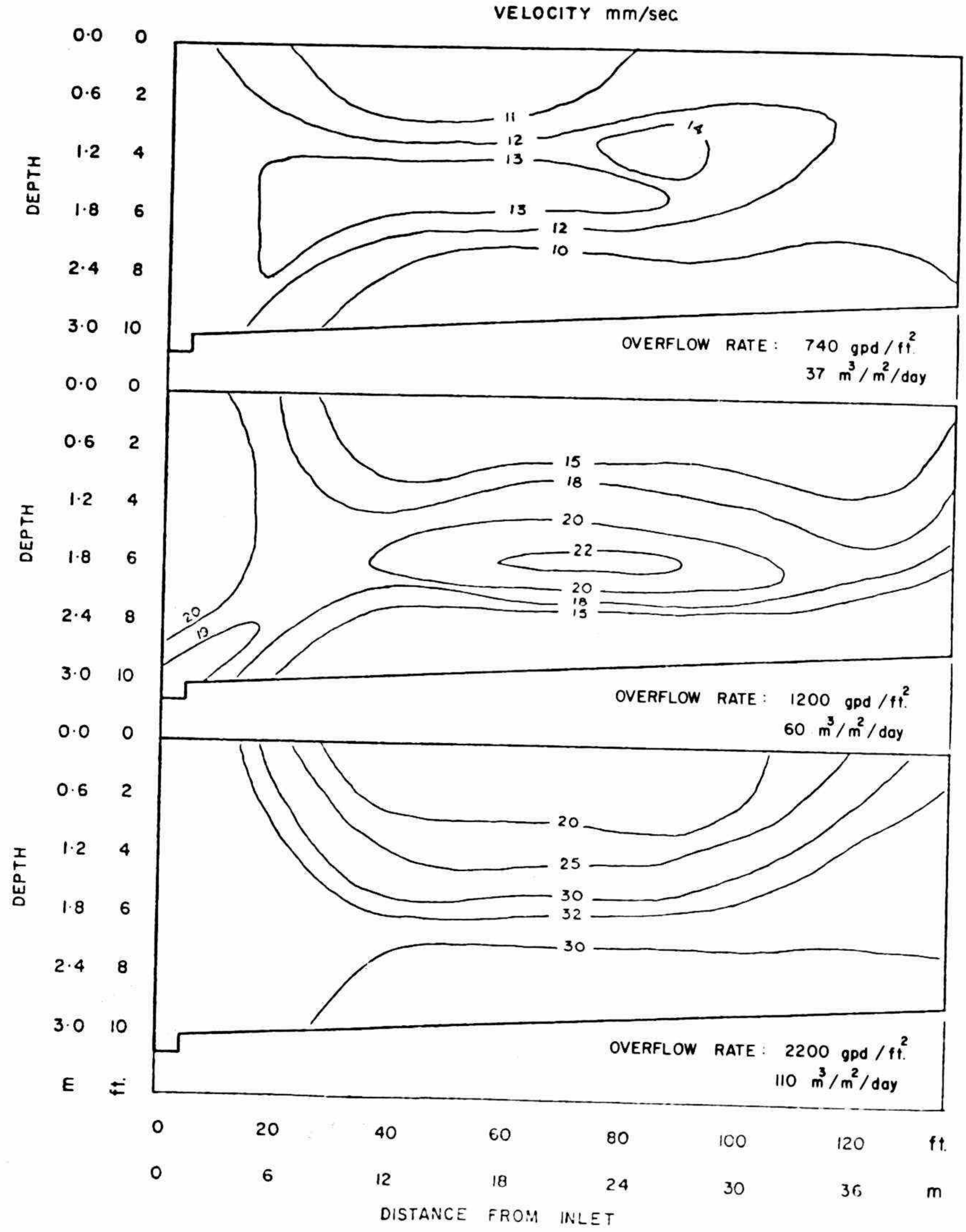


FIGURE 13. VELOCITY PROFILES AT SARNIA

Figures 25a and 25b show the effect of hydraulic loading (overflow rate and average resultant velocity, respectively) on the clarification efficiency. These figures summarize the results of this chapter and present them in a conventional and simple form. Figure 26 includes actual detention time as a parameter, which allows a visual assessment of the relative importance of overflow rate and actual detention time on the effluent quality.

9.2 Discussion of Results

9.2.1 Velocity profiles at Sarnia

It is difficult to illustrate flow patterns from the non-directional velocities. The magnitudes of the velocities shown are the resultants of the velocity components in three principal directions. The major velocity component was in the plane shown. With this caution the velocity profiles shown in Figure 13 indicated that:

(i) Velocities were highest at about the mid-depth (between 4 to 7 ft or 1.2 to 2.1 m) of the tank. (Average depth of tank 9 ft or 2.7 m).

(ii) With an increase in overflow rate, the local velocities increased about proportionately but the general pattern of velocities remained the same.

(iii) With three tanks in operation (overflow rate about 740 gpd/ft^2 or 37 m^3/m^2/day), the average of maximum velocity was found to be 14 mm/sec, with two tanks (1200 gpd/ft^2 or 60 m^3/m^2/day) about 22 mm/sec, and with one tank (overflow rate 2200 gpd/ft^2 or 110 m^3/m^2/day) about 32 mm/sec.

9.2.2 Suspended solids profiles at Sarnia

The perusal of Figures 14, 15 and 16 shows that:

(i) The addition of chemical shifts the profiles towards the inlet. In other words, when chemicals were added, the settling rate increased and clarification was accomplished within a shorter length of the tank and therefore within shorter detention time. Best results were achieved when both ferric chloride and polymer were added.

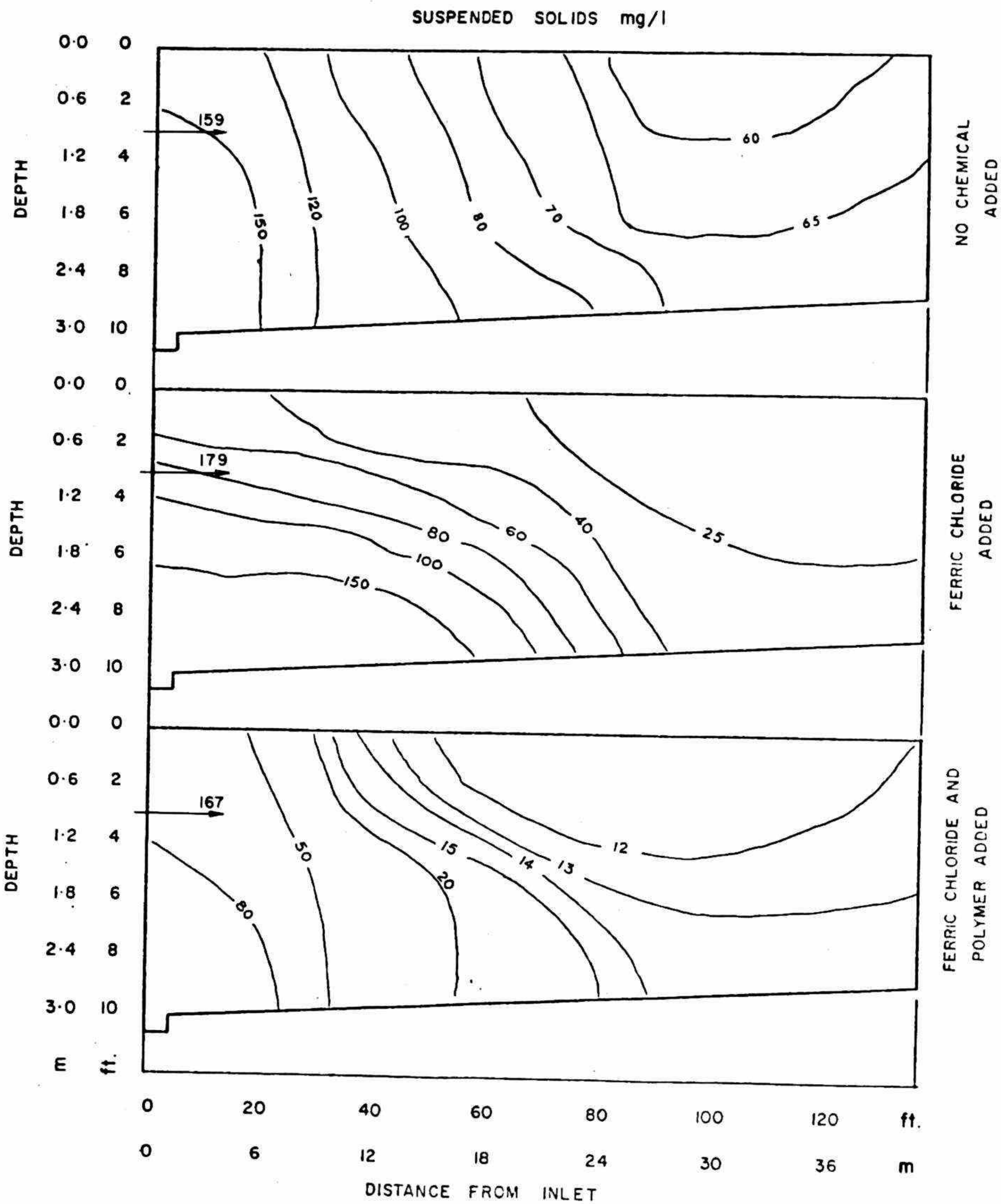


FIGURE 14. SUSPENDED SOLIDS PROFILES AT SARNIA
Overflow Rate: 740 gpd/ft^2 (37 m^3/m^2/day)

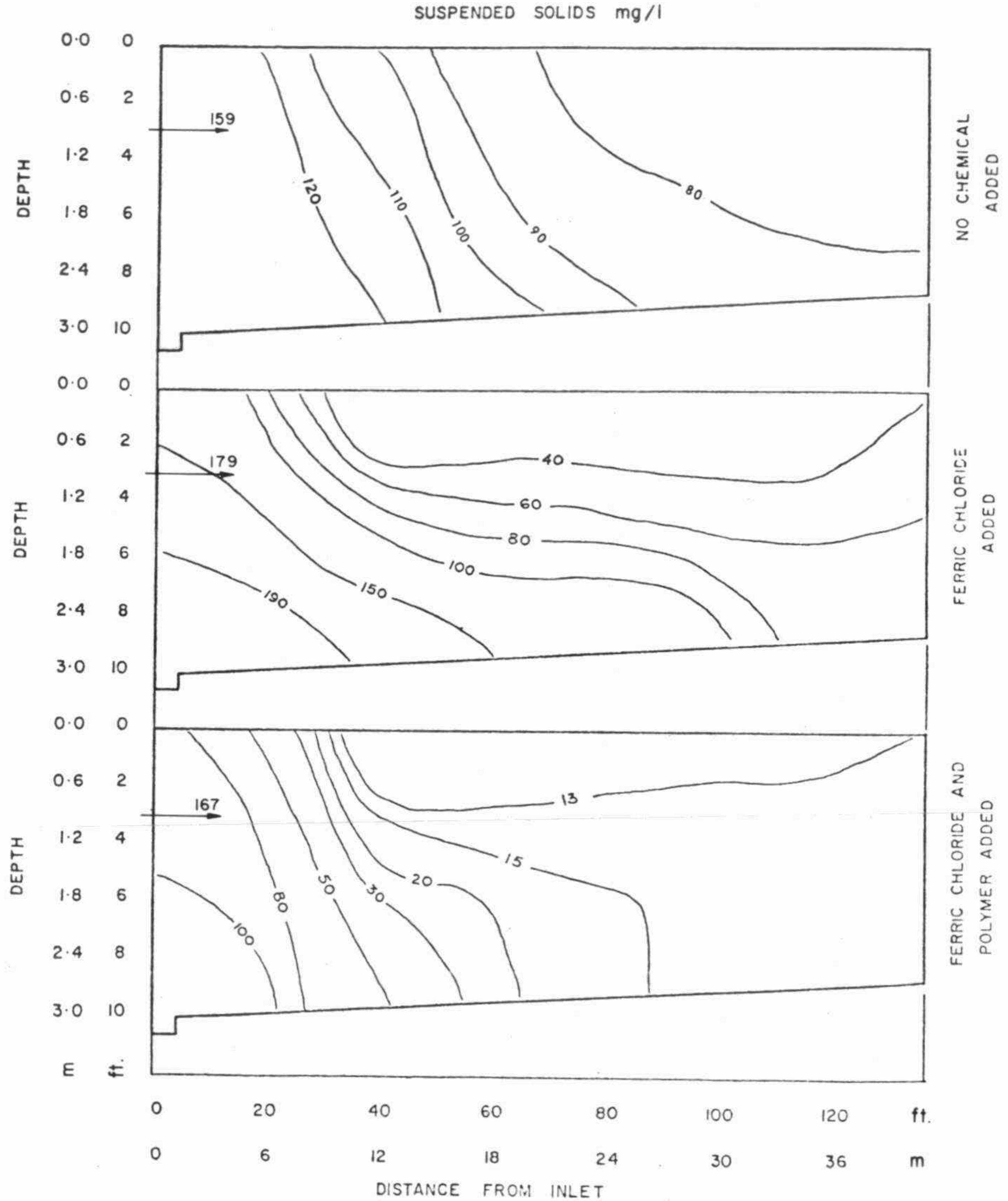
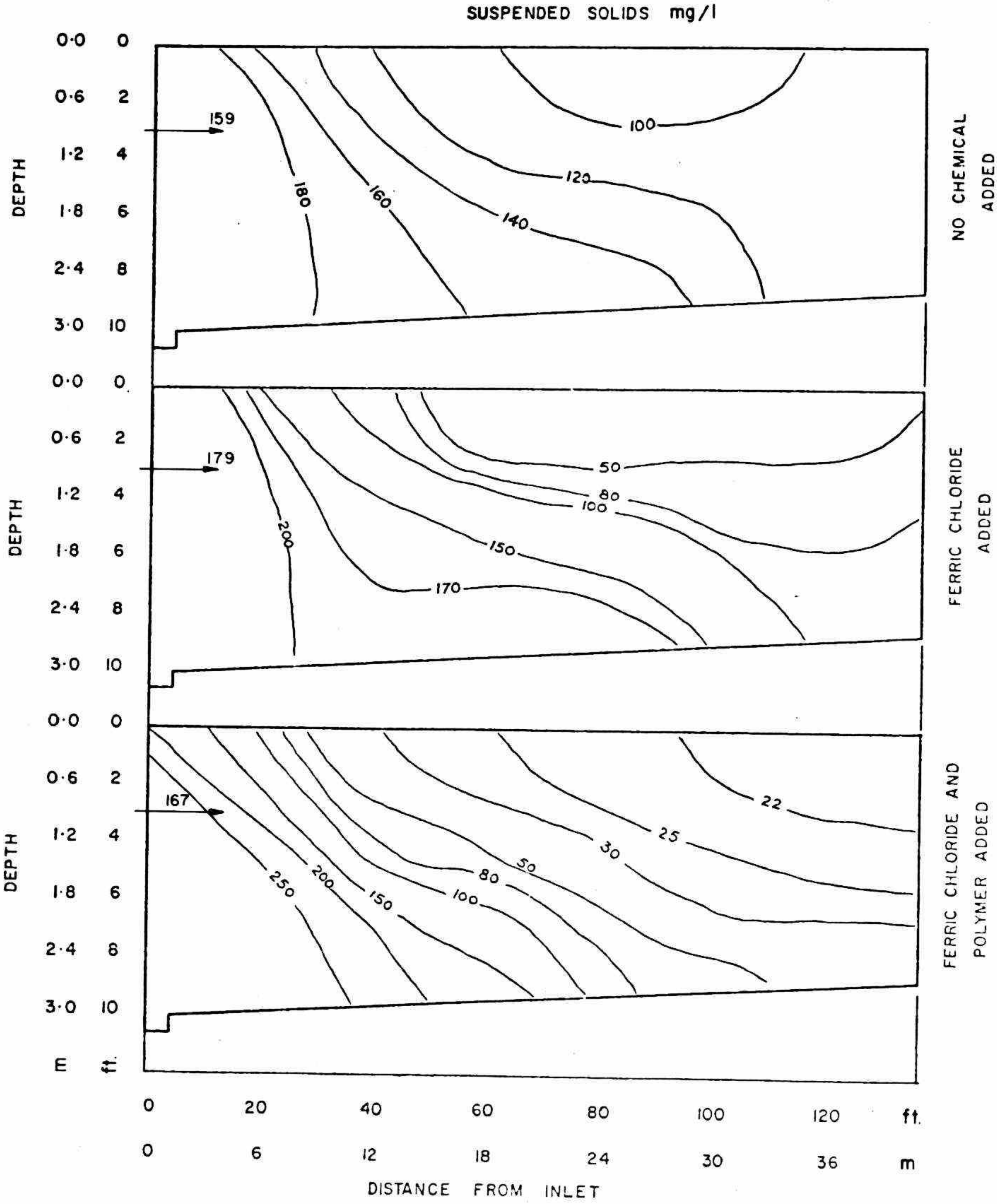


FIGURE 15. SUSPENDED SOLIDS PROFILES AT SARNIA
Overflow Rate: 1200 gpd/ft^2 (60 m^3/m^2/day)



F 16. SUSPENDED SOLIDS PROFILES AT SARNIA
Overflow Rate: 2200 gpd/ft^2 (110 m^3/m^2/day)

(ii) As the overflow rate increased (and the detention time decreased) the suspended solids profiles shifted towards the outlet end of the tank, showing decreased removal.

(iii) When the plant was operated on three, and two settling tanks (overflow rate 700-1200 gpd/ft^2 or 35-60 m^3/m^2/day), most of the settling occurred within the first half of the tank.

(iv) When only one tank was in operation (overflow rate about 2200 gpd/ft^2 or 110 m^3/m^2/day, most of the settling occurred within the first 3/4 of the tank.

(v) There was no significant adverse effect on effluent quality when the plant was operated on only one tank with chemical addition.

It should, however, be remembered here that when the overflow rates were increased by running the plant on three, two, and one tank, there was a proportionate decrease in the detention time also. The suspended solids profiles, therefore, depict the combined effect of increasing overflow rate and decreasing detention time. With one tank in operation, the actual detention time was about 26 minutes (theoretical - 37 minutes), and t_i about 15 minutes.

Furthermore, the increase in overflow rate was associated with an increase in local velocities. With one tank in operation, the average maximum intensity of velocity increased to 32 mm/sec.

From the above, it can be summarized that, at Sarnia the overflow rates (up to about 2200 gpd/ft^2 or 110 m^3/m^2/day) do not have any significant effect on the effluent quality as long as the actual detention time is about 30 minutes or more, and intensity of velocity in the main stream not more than 30 mm/sec, particularly when chemicals were added.

9.2.3 Velocity profiles at Windsor

It should be remembered again that the elevation of the tank shown here is not in its true proportion and therefore, the profiles will look steeper than they really are.

The velocity profiles in Figure 17 show that:

(i) It is difficult to determine the flow pattern from the velocity profiles measured at Windsor. In part this may

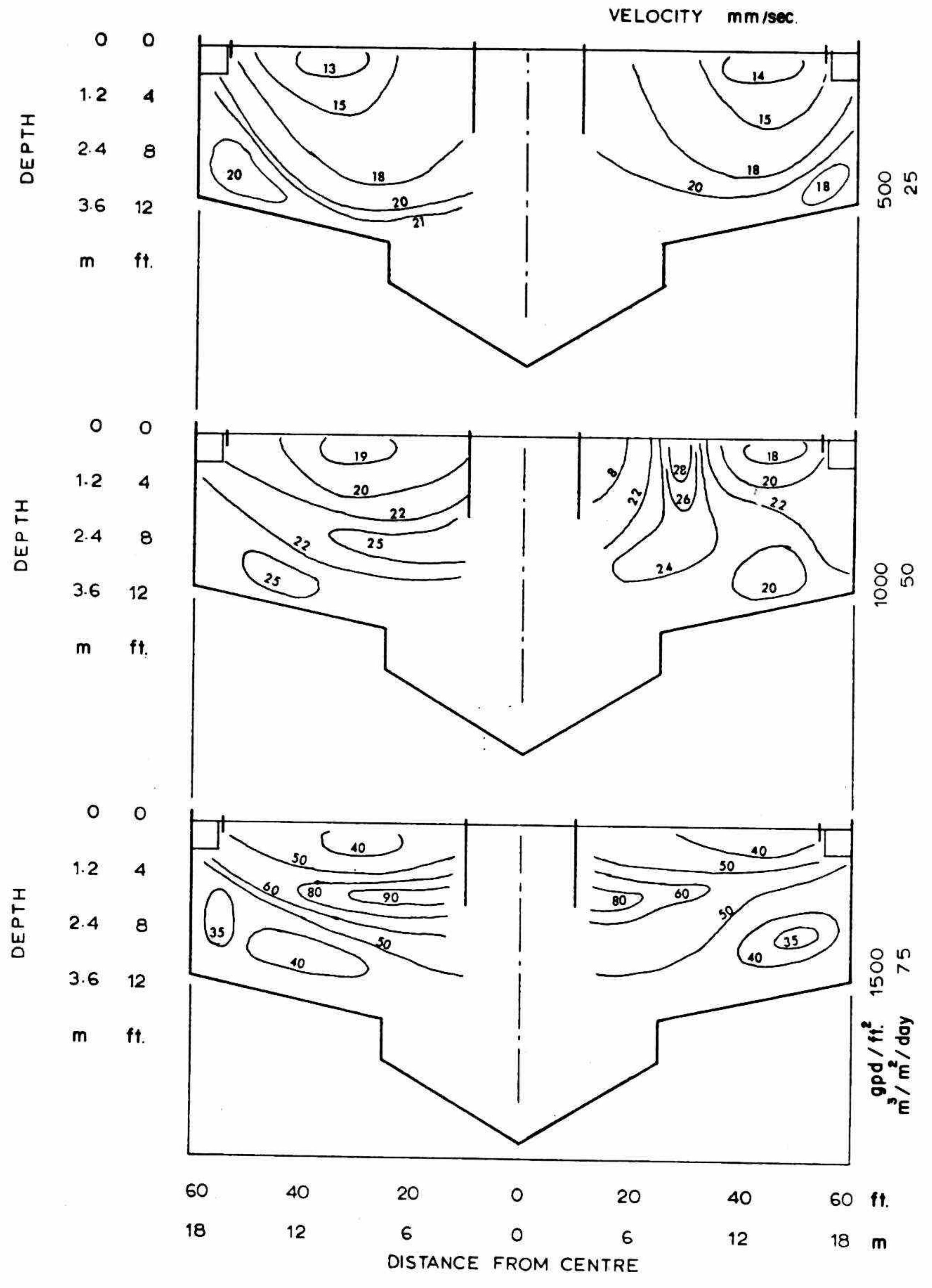


FIGURE 17. VELOCITY PROFILES AT WINDSOR

be caused by unsymmetrical results, caused by weir elevation differences. Some of the ineffective areas of the tank show surprisingly high velocities. Tracer studies indicate a "closed loop" water movement in these "stagnant" areas.

(ii) The intensity of prevalant velocities increased from about 13-20 mm/sec range to about 40-60 mm/sec range when the overflow rate increased from 500 to 1500 gpd/ft^2 (25 to 75 m^3/m^2/day).

(iii) For a comparable overflow rate and detention time, the local velocities in the circular tank in Windsor were considerably higher than at Sarnia, particularly at high overflow rates. This was due to the effect of short-circuiting in the Windsor tank.

(iv) Serious washout resulted when the plant was run on one tank (overflow rate about 2000 gpd/ft^2 or 100 m^3/m^2/day) and, therefore, no tests were performed with one tank in operation. The washout occurred, most likely, because of a) the small 'actual detention time' and/or b) very high velocities in the settling tank.

9.2.4 Suspended solids profiles at Windsor

Figures 18, 19, and 20 show that:

(i) For any overflow rate, the effect of chemical addition is to shift the suspended solids profiles downwards and inwards, showing increased removal.

(ii) As the overflow increased, (and the detention time decreased) the profiles moved upwards and outwards, which indicates decreased removal.

(iii) When ferric chloride and polymer were added, the change in overflow rates up to about 1500 gpd/ft^2 (75 m^3/m^2/day) did not affect significantly the effluent quality. The actual detention time, at this limiting overflow rate, was about 27 minutes (theoretical - 67 minutes) and local velocity range was 40-60 mm/sec.

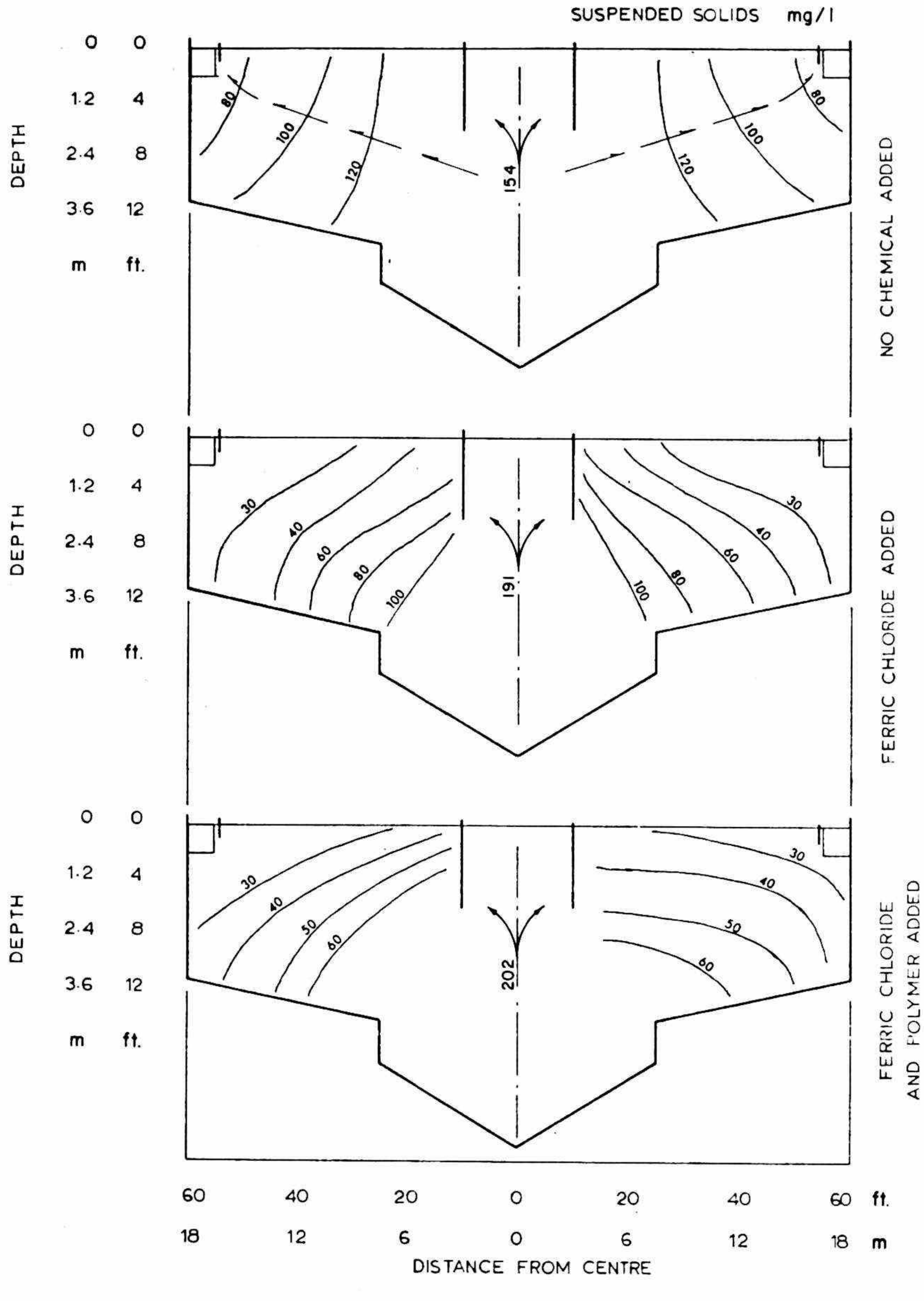


FIGURE 18. SUSPENDED SOLIDS PROFILES AT WINDSOR

Overflow Rate: 500 gpd/ft^2 (25 m^3/m^2/day)

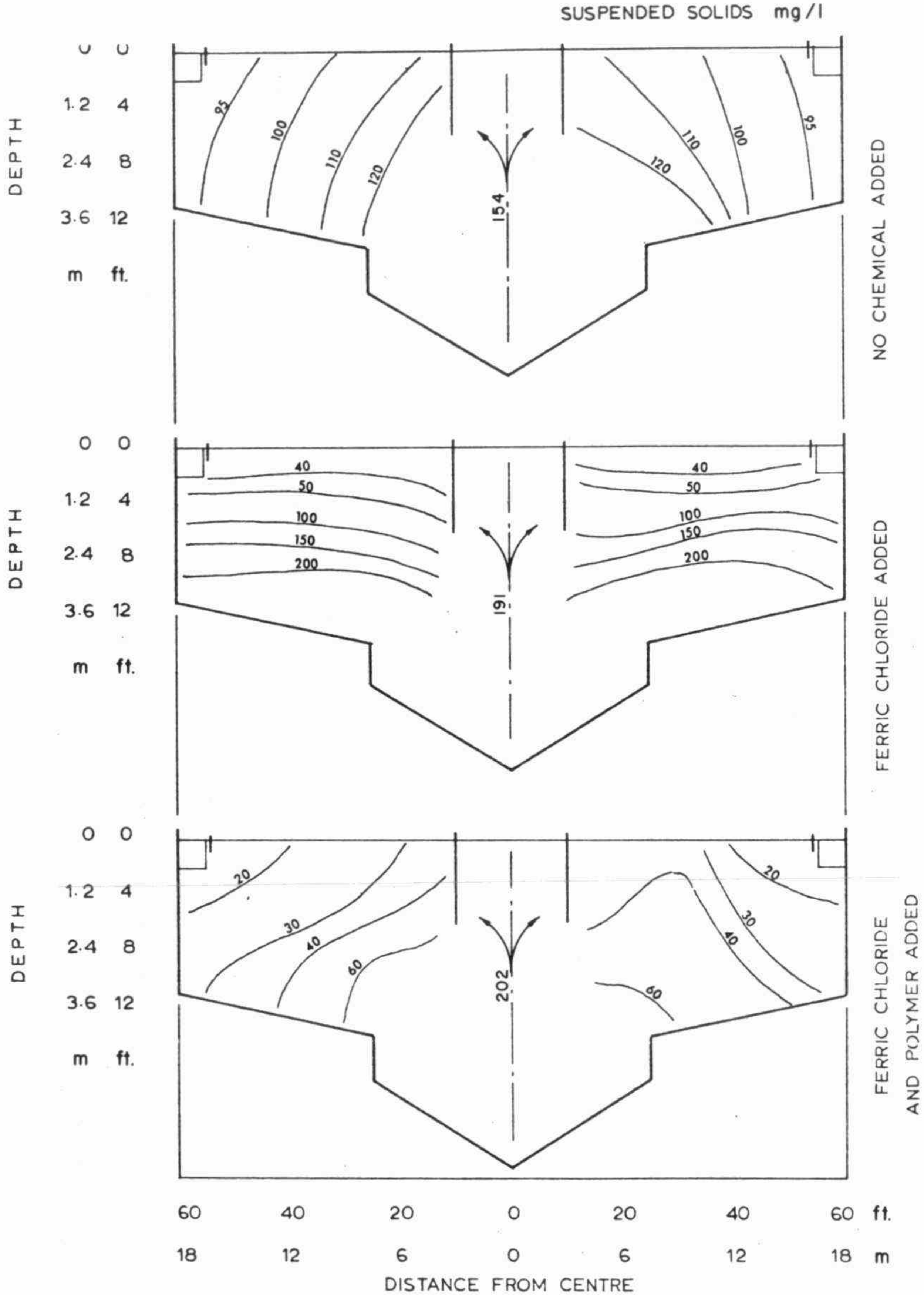


FIGURE 19. SUSPENDED SOLIDS PROFILES AT WINDSOR
Overflow Rate: 1000 gpd/ft^2 (50 m^3/m^2/day)

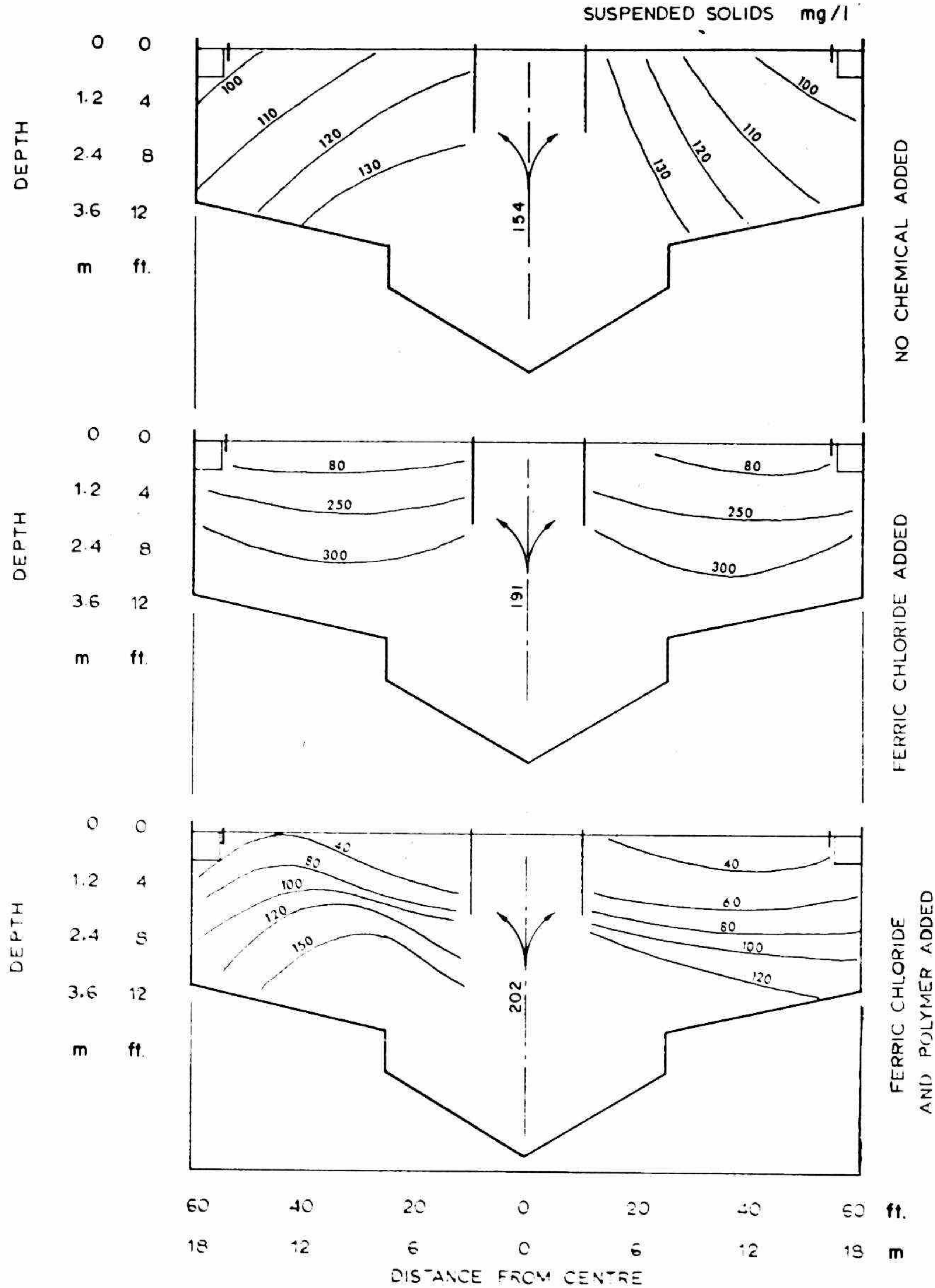


FIGURE 20. SUSPENDED SOLIDS PROFILES AT WINDSOR
Overflow Rate: 1500 gpd/ft^2 (75 m^3/m^2/day)

(iv) When the overflow rate was increased beyond 1500 gpd/ft^2 (75 m^3/m^2/day) the effluent quality started deteriorating very fast.

(v) From the above, it can be deduced that the effect of overflow rate on the effluent quality was quite small as long as the actual detention time was about 30 minutes or more, and the velocities in the settling zone were less than about 40-60 mm/sec. In this case, the actual detention time criterion matches that found at Sarnia.

(vi) The Windsor effluent quality, in general, was inferior to that in Sarnia. This is most likely caused by the fact that minimum flow-through time was much smaller in Windsor than in Sarnia. This point will be discussed further in Section 10.

9.2.5 Velocity and suspended solids profiles at Burlington

The form of velocity and suspended solids profiles at Burlington were generally the same as in Windsor, and most of the comments made under the Windsor study are generally applicable here as well. It should be noted particularly that, with the ferric chloride and polymer addition, the effluent quality was not affected significantly, even when the overflow rate was increased to as high as 2000 gpd/ft^2 (100 m^3/m^2/day) and detention time decreased to as low as 24 minutes.

It should, however, be pointed out that the pilot settling tank in Burlington is an up-flow rather than a horizontal-flow clarifier, because of its small radius/depth ratio. The settling process in this tank could be quite different from that in the column or horizontal-flow tanks. In this case, the sweeping action of flocs and sludge blanket probably played a significant role in the clarification process.

The settling study in the pilot plant was conducted to develop a dispersion model, and the results shown here may not be applicable to larger plants, particularly with horizontal flow system.

9.2.6 Effect of hydraulic loading on clarification

During the plant study when the hydraulic loading of the settling tanks was increased by increasing the flow through the tanks, it was

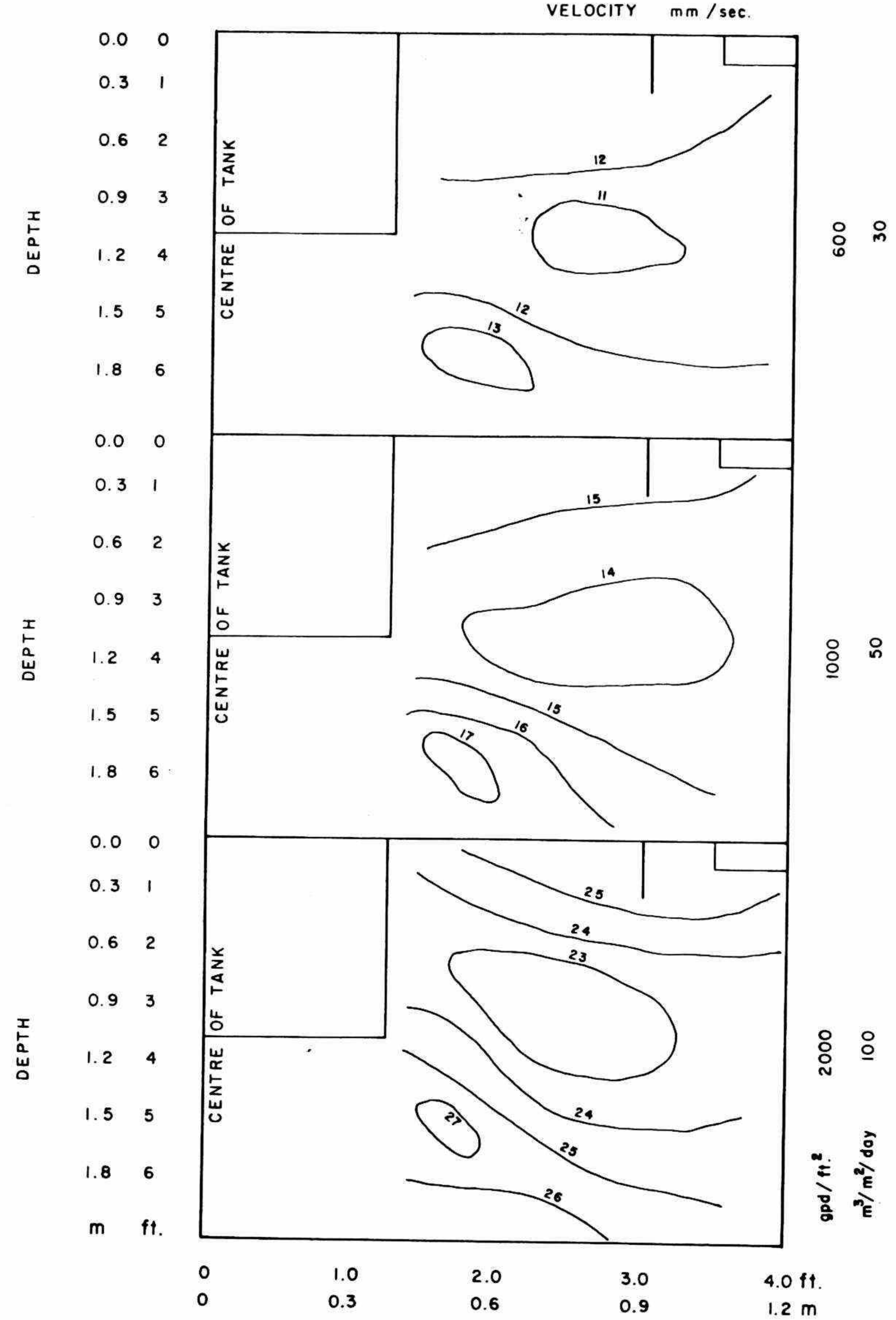


FIGURE 21. VELOCITY PROFILES AT BURLINGTON

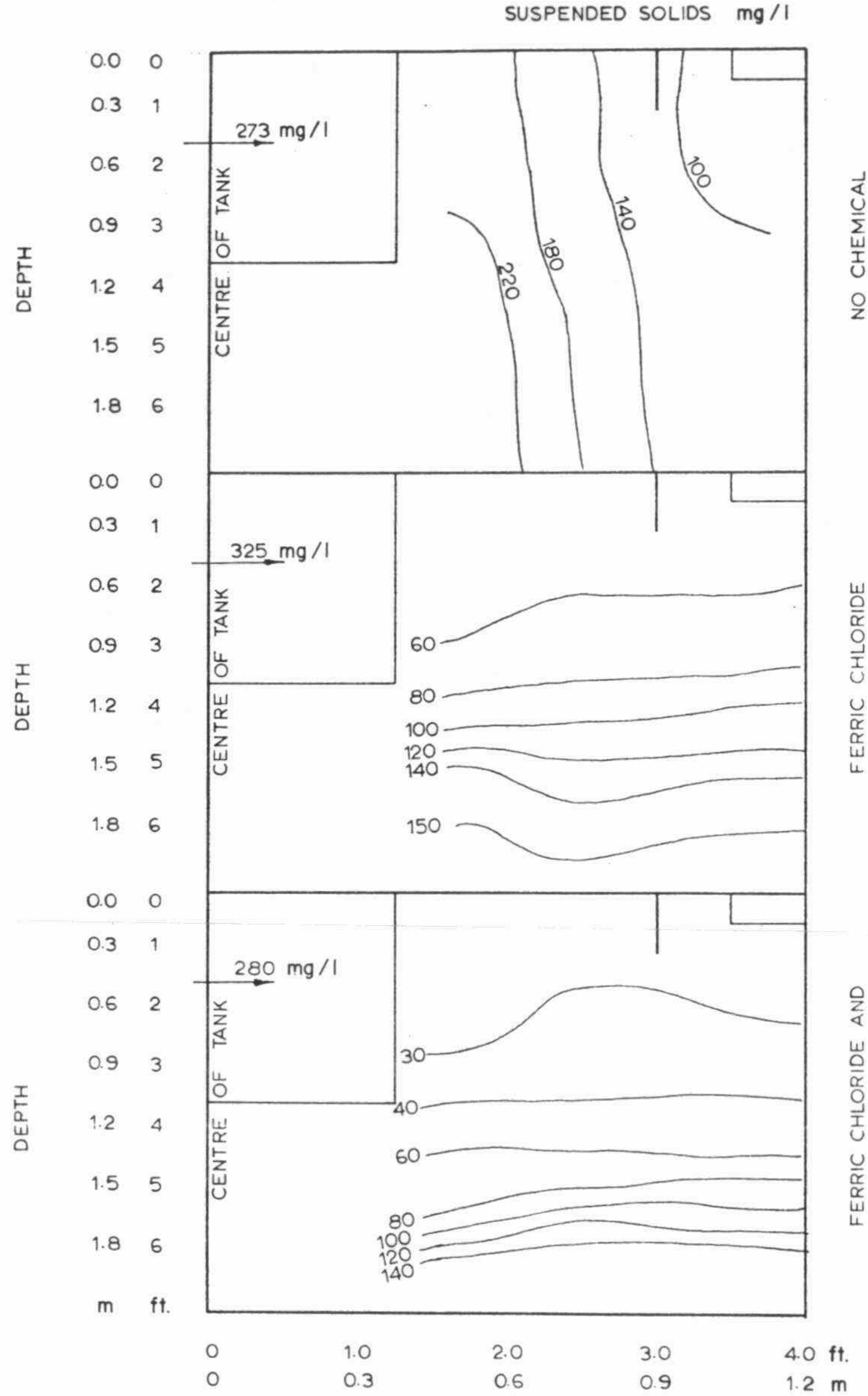


FIGURE 22. SUSPENDED SOLIDS PROFILES AT BURLINGTON
Overflow Rate: 600 gpd/ft^2 (30 m^3/m^2/day)

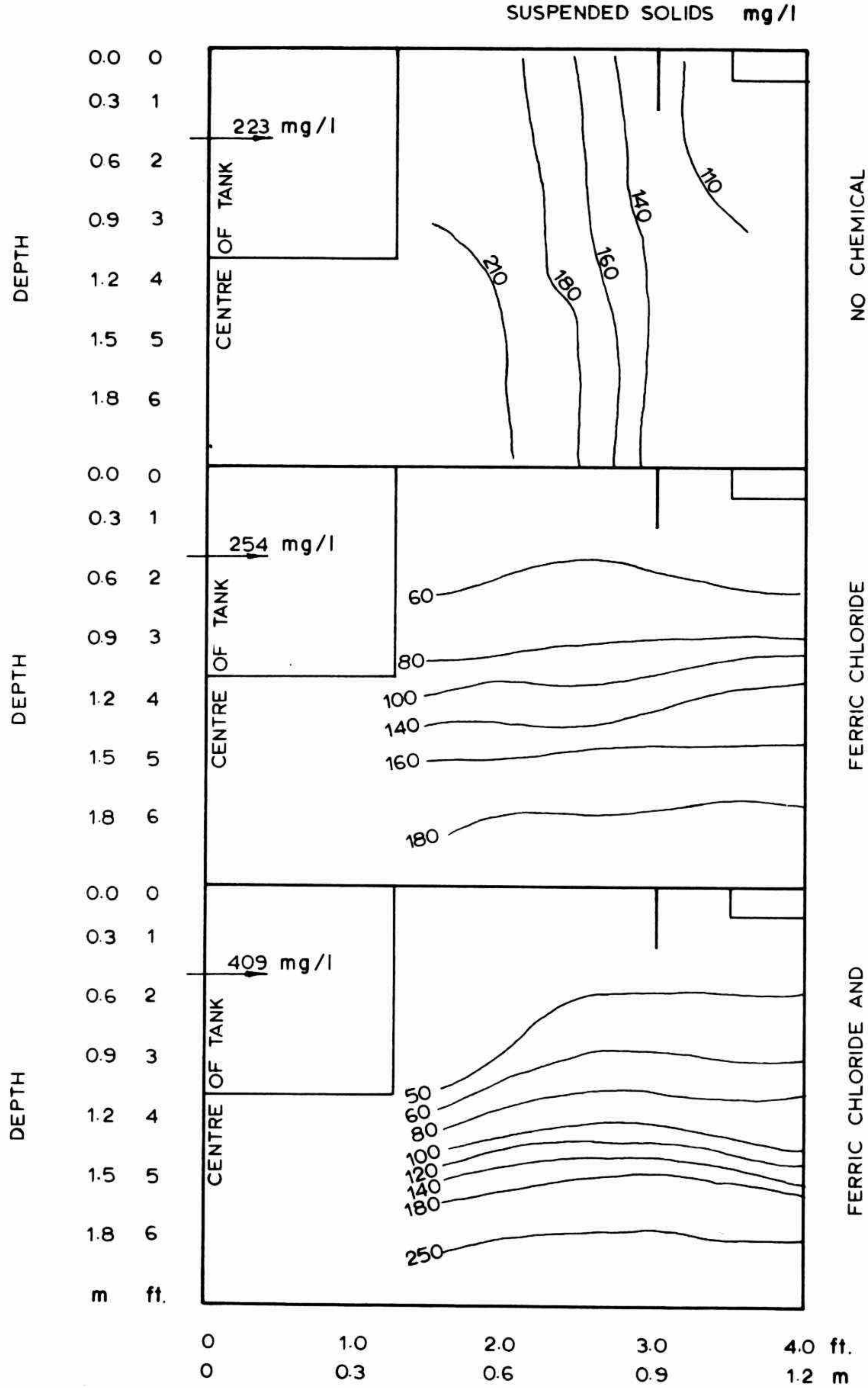


FIGURE 23. SUSPENDED SOLIDS PROFILES AT BURLINGTON

Overflow Rate: 1000 gpd/ft^2 (50 m^3/m^2/day)

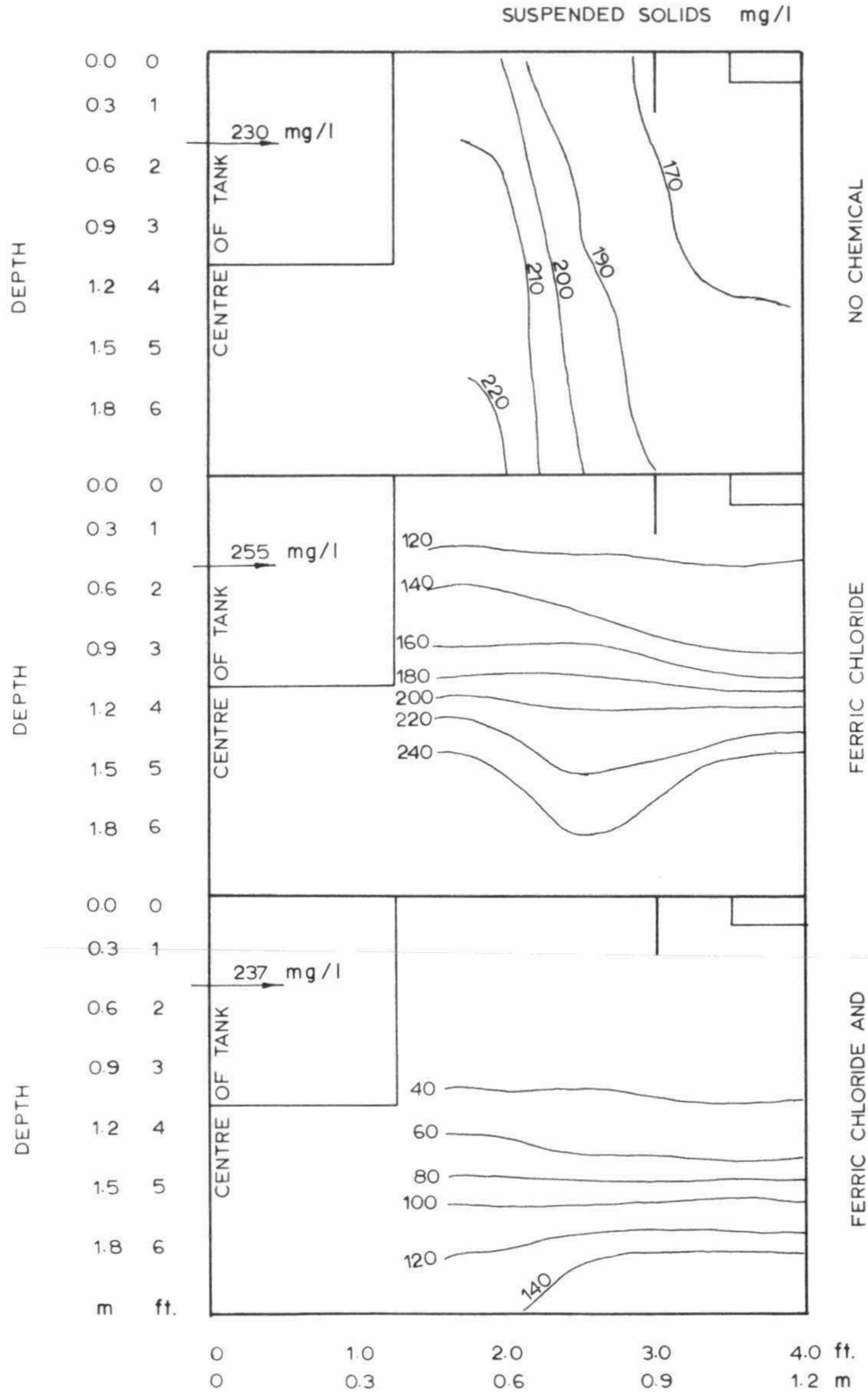


FIGURE 24. SUSPENDED SOLIDS PROFILES AT BURLINGTON

Overflow Rate: 2000 gpd/ft^2 (100 m^3/m^2/day)

associated with corresponding changes in the other hydraulic parameters as follows:

- increase in overflow rate,
- increase in velocity and turbulence,
- decrease in theoretical and actual detention time.

Figures 25a and 25b show the effect of these interdependent variables which have been lumped together under one parameter, i.e., overflow rate or velocity. This is an oversimplified form which has been adopted by the researchers in the presentation of the results on plant performance.

Figure 25 (a and b) shows that:

(i) As the hydraulic loading in the settling tank was increased, the effluent quality deteriorated.

(ii) The effect of hydraulic loading was reduced significantly when ferric chloride and polymer were added.

(iii) For the same hydraulic loading, the Windsor settling tanks produced an inferior effluent.

(iv) When hydraulic loading was increased by running the plant on four, three, two and one tank, the velocities in the Sarnia tanks varied within a small range (15-30 mm/sec). In Windsor, the velocities varied over a large range (15-60 mm/sec) even though the hydraulic loading was lower. Burlington hydraulic loading data were similar to those of Sarnia.

Figure 26 replots data from Figure 25a but includes actual detention time as a parameter. This allows a visual assessment of the effect of overflow rate and actual mean detention time (independent of each other) on clarification efficiency. This figure has been developed from the data obtained from Sarnia and Windsor settling tanks which have different overflow rates for the same <u>actual</u> mean detention time. (The Burlington settling tank, because of its upflow characteristics and high variations in hydraulic efficiency, has been excluded from this particular analysis.)

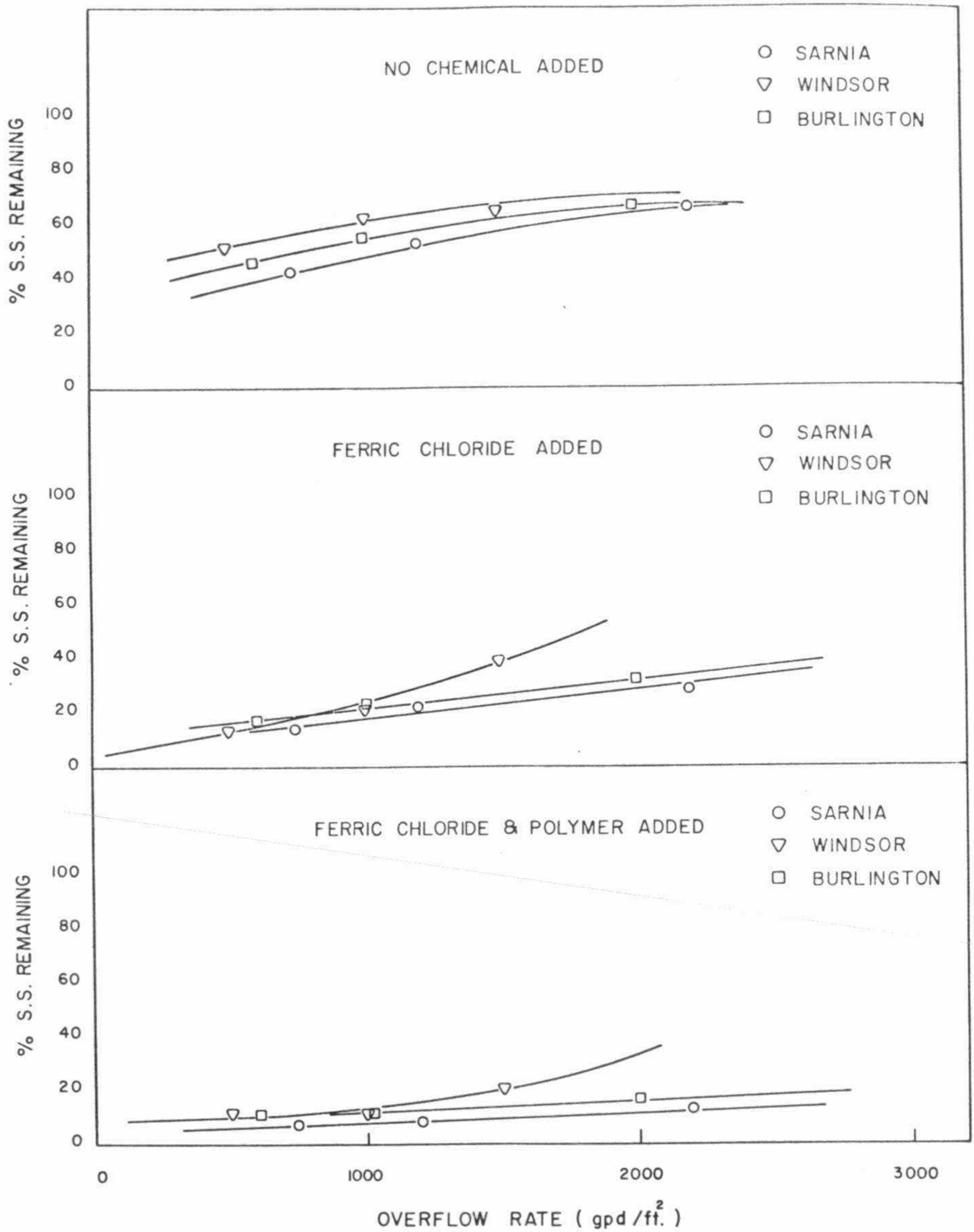


FIGURE 25a. EFFECT OF HYDRAULIC LOADING (OVERFLOW RATE) ON CLARIFICATION EFFICIENCY

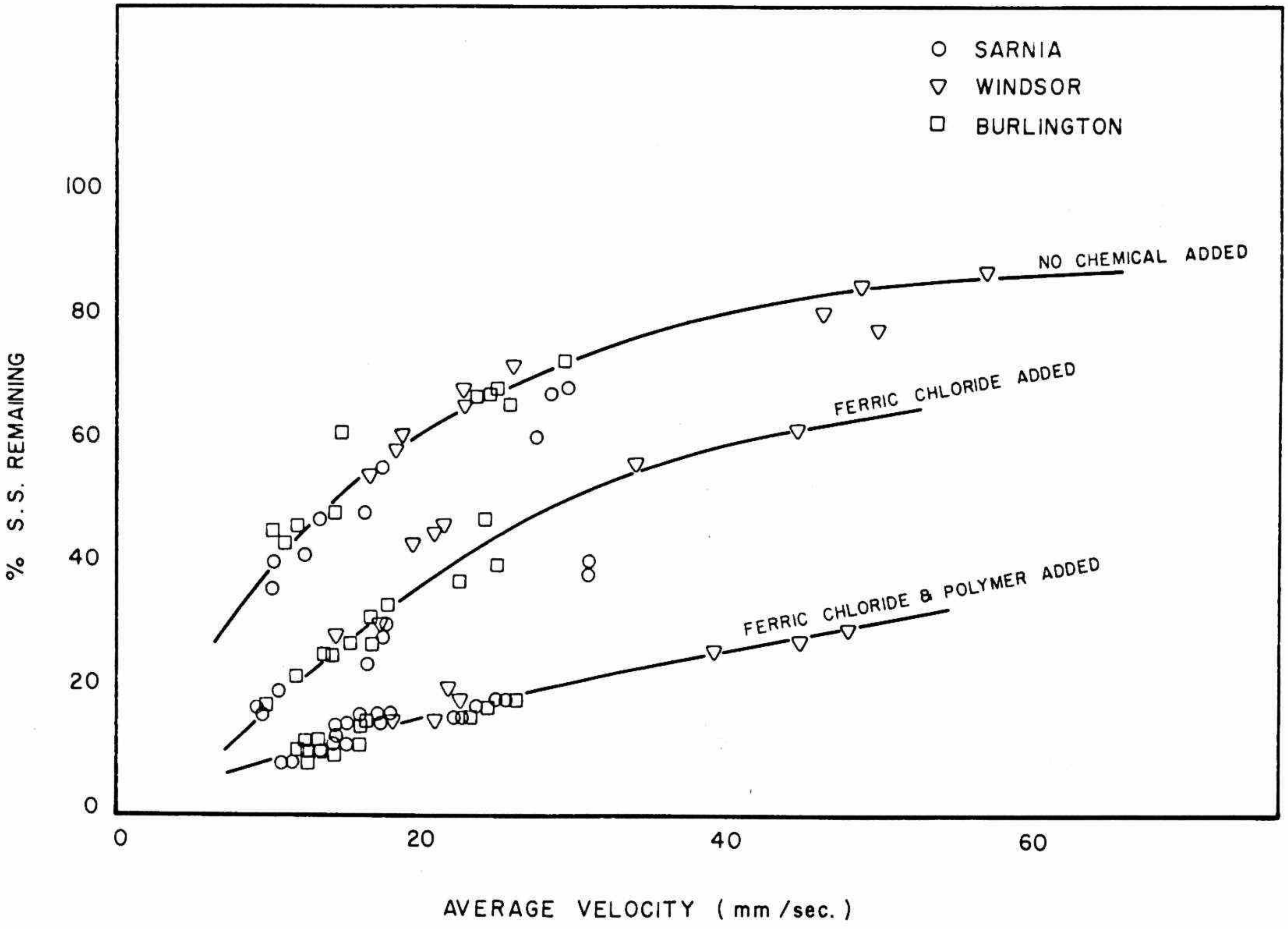


FIGURE 25b. EFFECT OF HYDRAULIC LOADING (AVERAGE VELOCITY) ON CLARIFICATION EFFICIENCY

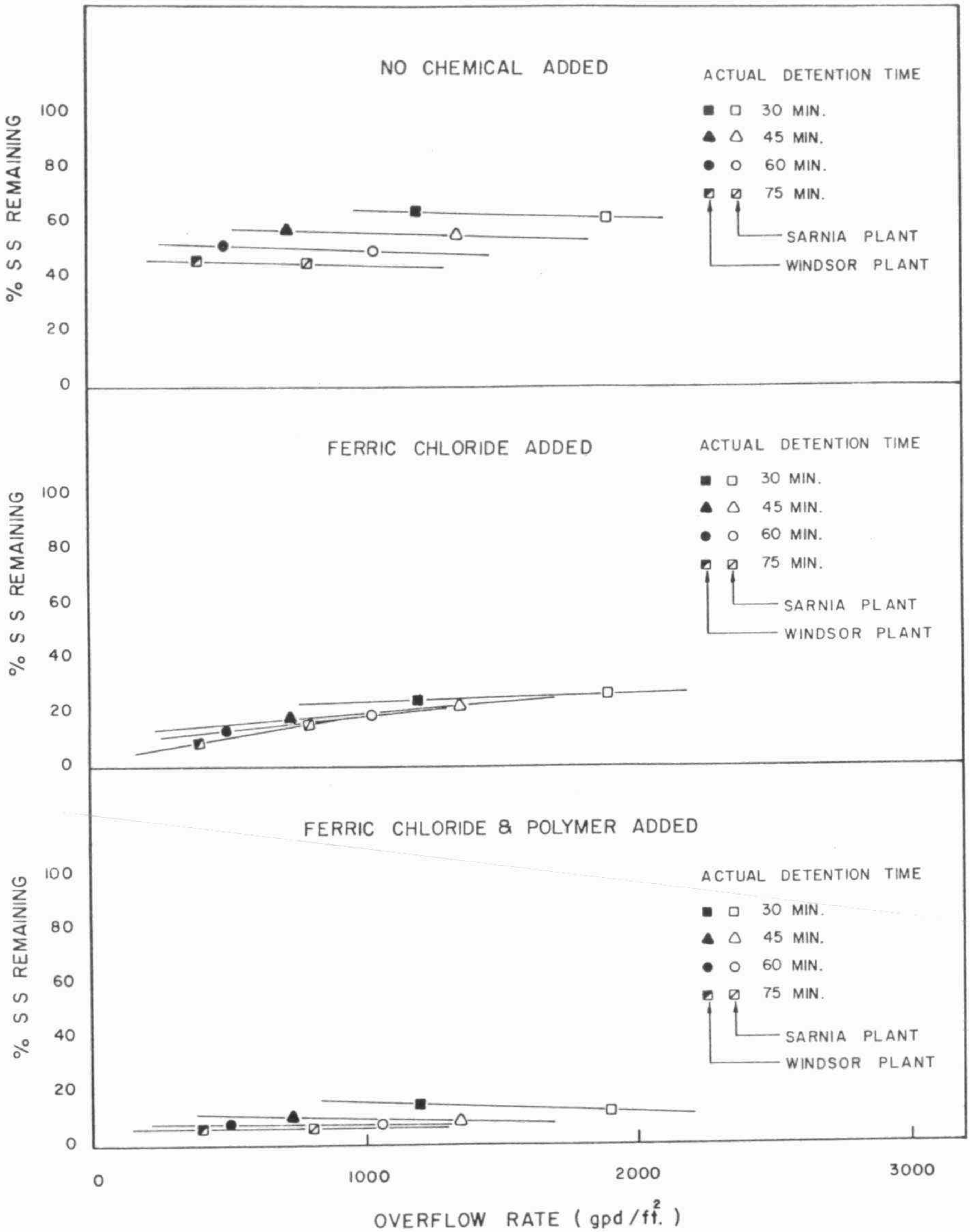


FIGURE 26. EFFECT OF OVERFLOW RATE AND ACTUAL MEAN DETENTION TIME ON CLARIFICATION EFFICIENCY

Figure 26 shows that:

(i) For a given <u>actual</u> mean detention time, increases in overflow rate had little effect on effluent quality.

(ii) For a given overflow rate, the effluent quality deteriorated with a decrease in actual mean detention time. The minimum measured mean detention time was about 30 minutes. It is expected that lower values would seriously affect effluent quality.

(iii) When ferric chloride and polymer were added, the effluent quality improved slightly when actual mean detention time was increased from 30 to 75 minutes. Without chemical addition, the effect of detention time was more significant.

10 EMPIRICAL MODELS

This phase of the study was conducted from two separate approaches with the common objective of developing design and performance parameters for settling tanks for the removal of physical-chemical flocs. As a result, two empirical models were developed, namely (i) Settling Model, and (ii) Dispersion Model. This first approach is based on:

a) the study of the settling characteristics of suspensions in settling columns under quiescent conditions, with and without chemical addition,

b) the study of the hydraulic characteristics of settling tanks under various hydraulic loadings,

c) the development of a relationship between (a) and (b) to depict the settling behaviour of physical-chemical flocs in a settling tank under continuous flow conditions, under various conditions of hydraulic loading and chemical addition.

The second approach is based on:

a) the measurement of concentration of suspended solids and intensity of velocities at a sufficient number of points in the settling tank, under various conditions of hydraulic loading and chemical addition,

b) the development of a dispersion model from the data collected, as described above, to study the effect of velocity and turbulence on the performance of settling tanks.

10.1 Settling Model

A model of a settling tank should account for the following factors:

A. a) the settling characteristics of suspensions,

b) the effect of flocculation due to difference in settling velocity of suspended particles,

c) the effect of flocculation due to turbulence,

d) the effect of overflow rate,

e) the effect of detention time,

f) the effect of depth of settling,

B. g) the hydraulic behaviour (efficiency) of settling tanks,

h) the effect of water turbulence, or velocity, on settling rate of suspensions.

In settling column analysis, all (except for (a) and (b) which were studied in combination) the factors listed under (A) were studied individually and evaluated. The results of these influencing factors were summarized earlier in Section 7 where they were presented by settling curves (S-curves) and Equation 3 or 4.

Factor (g) under category (B) was studied in Section 8 and presented by dispersion curve or C-curve, ti/T and tg/T indices, and ti and tg parameters.

The effect of factor (h) could not be evaluated directly or individually. In the settling column, the tests were carried out under quiescent conditions. In the actual tank, when the velocities were increased, these were associated with the increase in overflow rate and decrease in detention time. The changes in effluent quality (small or large depending on whether chemicals were added or not) as the result of change in velocities were, in fact, due to the combined effect of the changes in velocity, overflow rate and detention time. The combined effect of these three variables has, however, been accounted for in the C-curve, where the net effect of increased velocity was to push the front of C-curve further ahead (to left).

From the data, it has been estimated that, within the range of the velocities encountered in the studies in the settling zone of the tank, velocities have only a small effect on effluent quality. A comparison of effluent qualities predicted by this model and the actual tank was made without considering the net effect of the local velocities in the tank. The comparison was in close agreement.

In Windsor when the settling tank was operated up to 1500 gpd/ft^2 (75 m^3/m^2/day), no serious deterioration of effluent quality occurred (not any more than predicted by actual detention time criteria and S-curve) even though the prevalent velocities were in the range of 40-60 mm/sec. At higher flow rates the effluent quality deteriorated rapidly in response to short detention time (at 2000 gpd/ft^2 or 100 m^3/m^2/day, ti = 5 and tg = 21 minutes, as compared to those at Sarnia, ti = 16, and tg = 29).

After evaluating all the factors described earlier, it can be concluded that the performance of the settling tank can be predicted by superimposing the hydraulic efficiency of the tank onto the settling characteristics of suspensions; in other words, by superimposing the C-curve (with true dimensions) onto the S-curve. The quality of effluent can then be determined by summing up the concentration of suspended solids in various fractions of flow (area under C-curve defines the flow and area under S-curve determines suspended solids - see Figure 27a).

It can be proven that if the C-curve falls over the flat portion of the S-curve (where the S-curve is approximately a straight line), the concentration of suspended solids in the effluent can be read on the S-curve at the point of centre of gravity of the C-curve, that is, at time tg (see Figure 27b). For the proper performance of the tank, it is important that the C-curve should not penetrate into the steep part of S-curve. If it does, then it means that some part of flow will pass through the settling tanks with little removal of suspended solids. Therefore, under the above conditions, Equation 4 can be rewritten with the limitations stated below as follows:

$$S = \frac{S_o A}{(t_g)^n + A} \qquad (5)$$

Limitations:

- t_i, time interval for initial indication of tracer in effluent, should not be less than 15 minutes with chemical, and 30 minutes without chemical additions. This time is needed for flocculation, development and settling of flocs.
- for t_i values less than the above, calculate suspended solids in effluent directly from S-curve and C-curve, as discussed above.

10.1.1 Comparison of settling model and real tank performance

The effluent quality, as predicted from the settling model, was compared with the plant effluent at Sarnia, Windsor and Burlington, and is shown in Tables 8, 9 and 10, respectively. The results, in general, were in close agreement.

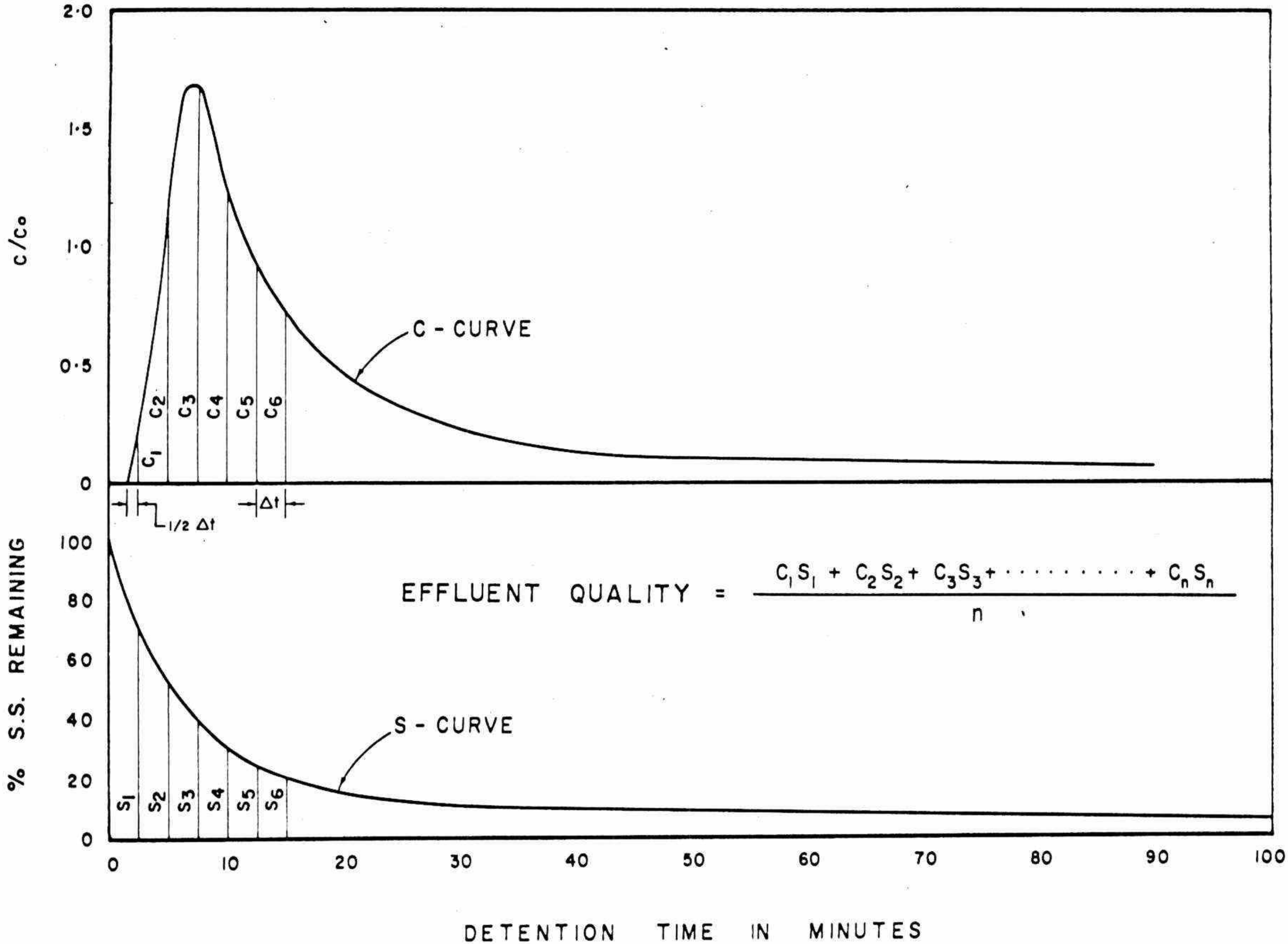


FIGURE 27a. PREDICTION OF EFFLUENT QUALITY BY SUPERIMPOSING C-CURVE ONTO S-CURVE (CASE 1)

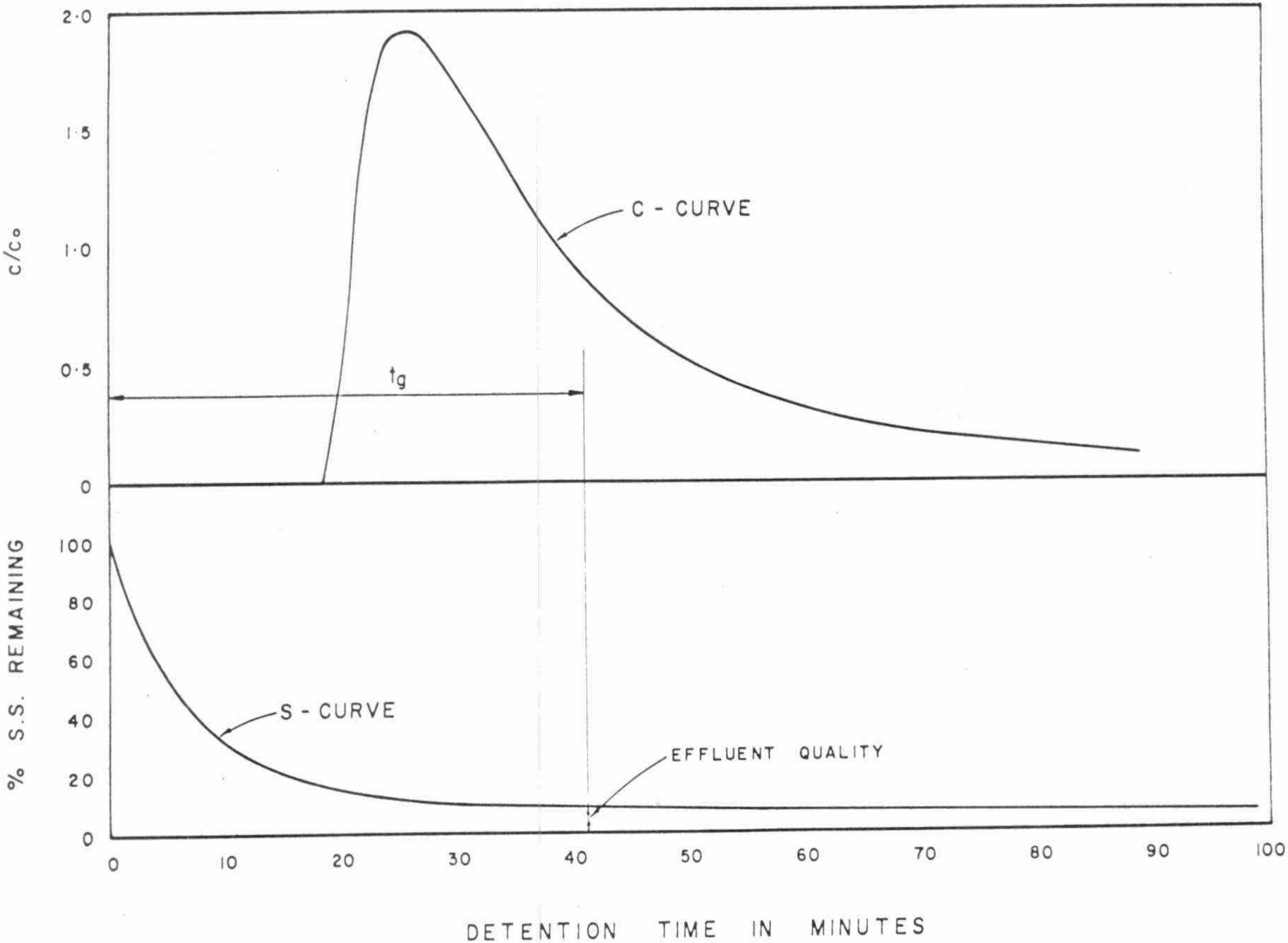


FIGURE 27b. PREDICTION OF EFFLUENT QUALITY BY ACTUAL MEAN DETENTION TIME (CASE 2)

TABLE 8. COMPARISON OF SETTLING MODEL AND REAL TANK PERFORMANCE AT SARNIA

Overflow Rate		Detention Time Minutes		Influent to Settling Tank (mg/l)	Effluent SS Remaining	
gpd/ft^2	$m^3/m^2/day$	Theor.	Actual		Real Tank	Model
		Without Chemical Addition				
740	37	110	80	Avg.	43%	48%
1200	60	69	51	159	53%	54%
2200	110	37	26		66%	64%
		With Ferric Chloride Addition				
740	37	110	80	Avg.	14%	15%
1200	60	69	51	179	22%	18%
2000	110	37	26		28%	29%
		With Ferric Chloride and Polymer Addition				
740	37	110	80	Avg.	7%	6%
1200	60	69	51	167	8%	8%
2200	110	37	26		13%	14%

TABLE 9. COMPARISON OF SETTLING MODEL AND REAL TANK PERFORMANCE AT WINDSOR

Overflow Rate		Detention Time Minutes		Influent to Settling Tank (mg/l)	Effluent SS Remaining	
gpd/ft^2	m^3/m^2/day	Theor.	Actual		Real Tank	Model
		Without Chemical Addition				
500	25	200	60	Avg.	52%	52%
1000	50	100	33	154	62%	61%
1500	75	67	27		65%	64%
		With Ferric Chloride Addition				
500	25	200	60	Avg.	13%	16%
1000	50	100	33	191	22%	23%
1500	75	67	27		39%	40%
		With Ferric Chloride and Polymer Addition				
500	25	200	60	Avg.	12%	9%
1000	50	100	33	202	11%	13%
1500	75	67	27		20%	20%

TABLE 10. COMPARISON OF SETTLING MODEL AND REAL TANK PERFORMANCE AT BURLINGTON

Overflow Rate		Detention Time Minutes		Influent to Settling Tank (mg/l)	Effluent SS Remaining	
gpd/ft^2	m^3/m^2/day	Theor.	Actual		Real Tank	Model
		With Chemical Addition				
600	30	110	42	Avg.	46%	57%
1000	50	66	36	242	56%	59%
2000	100	33	24		67%	66%
		With Ferric Chloride Addition				
600	30	100	42	325	17%	20%
1000	50	66	36	254	22%	22%
2000	100	33	24	255	32%	30%
		With Ferric Chloride and Polymer Addition				
600	30	110	42	280	11%	10%
1000	50	66	36	409	12%	11%
2000	100	33	24	237	17%	16%

To further elaborate on the reliability and performance of the model, suspended solids profiles in the tanks were compared with those developed from the model. For this purpose, mean suspended solids for any cross-section of the tank were plotted against actual detention time. The ratio of actual and theoretical detention time for any stretch or length of a particular tank was assumed to be the same as for the whole tank.

For the Sarnia tank, concentrations of suspended solids at mid-depth (4 ft or 1.2 m from the surface of water) and at various locations along the length of the tank at various hydraulic loadings were plotted over the graph of the particular model. Figure 28 shows the results for the various conditions of chemical treatment. It can be seen from the figure that, as the suspensions proceeded through the tank, their pattern and rate of settling was about the same as shown by the model.

For the Windsor tank, concentrations of suspended solids were taken along the diagonal (along the mean direction of flow as shown by arrows in Figure 18). The results are shown in Figure 29 for various chemical additions. Figure 29 also shows that, again, the suspensions in the tank were clarified at approximately the same rate as is given by the model.

10.1.2 Discussion

Tables 8, 9 and 10 show close agreement between the effluent quality from the actual settling tanks and effluent quality predicted by the settling model.

The results show that the quality of effluent from Sarnia settling tank was better and more stable than in Windsor, and changed slightly with the increase in overflow rate. This is because the entire C-curve for this tank falls over the flatter portion of the S-curve, showing thereby that there was no serious short-circuiting or dispersion even at an overflow rate as high as 2000 gpd/ft^2 or 110 m^3/m^2/day (ti = about 15 minutes, tg = 26 minutes, and T = 37 minutes).

At Windsor, on the other hand, the effluent quality started deteriorating even before the overflow rate reached 1500 gpd/ft^2 or 74 m^3/m^2/day because of short-circuiting, etc. This is evident from the hydraulic parameters at this overflow rate (ti = 7 minutes, and tg = 27 minutes). This means that about 20 percent of the flow received only 7-15 minutes detention and reached the outlet with little suspended solids

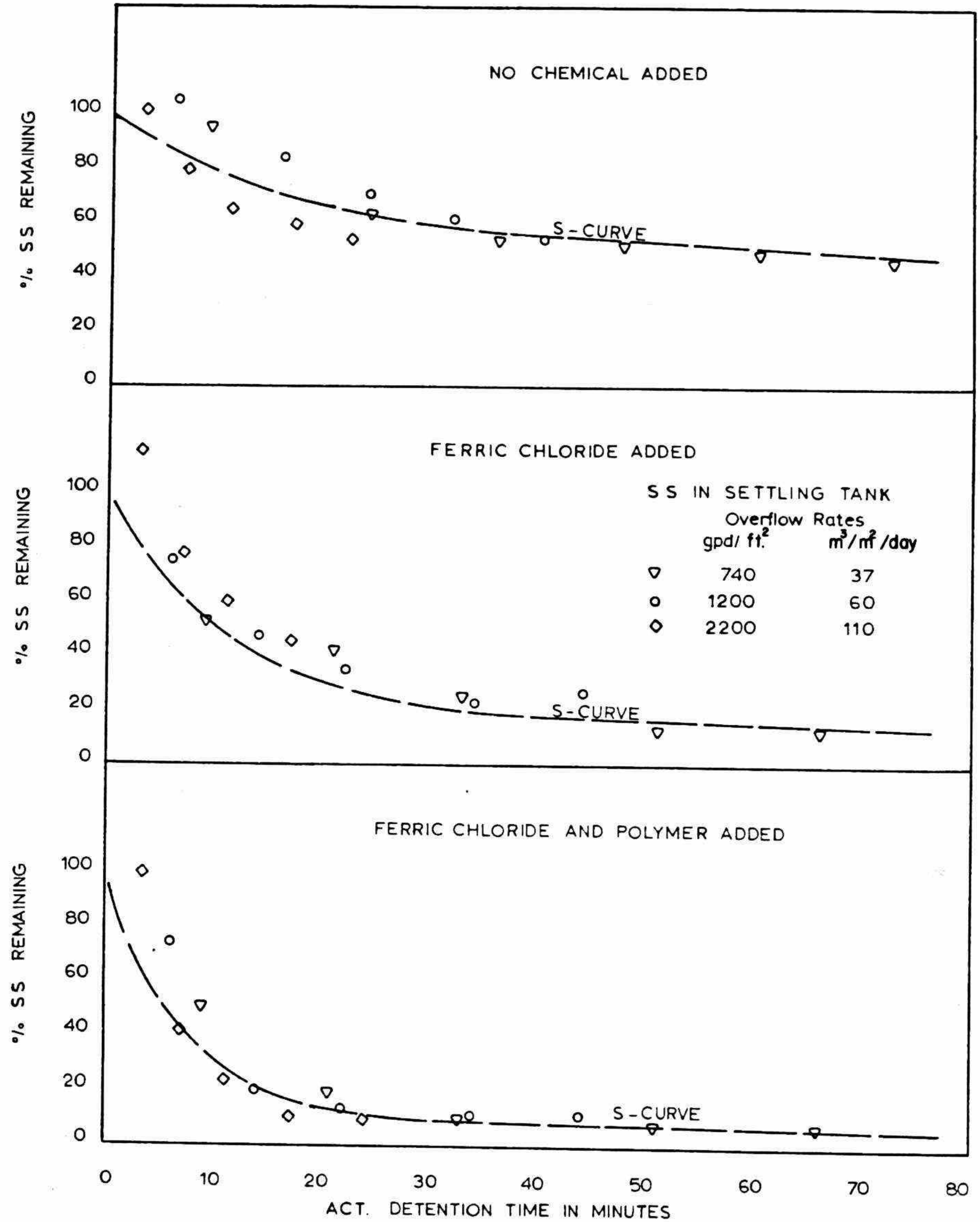


FIGURE 28. SETTLING BEHAVIOUR OF PHYSICAL-CHEMICAL FLOCS AT SARNIA: Settling Model - Real tank

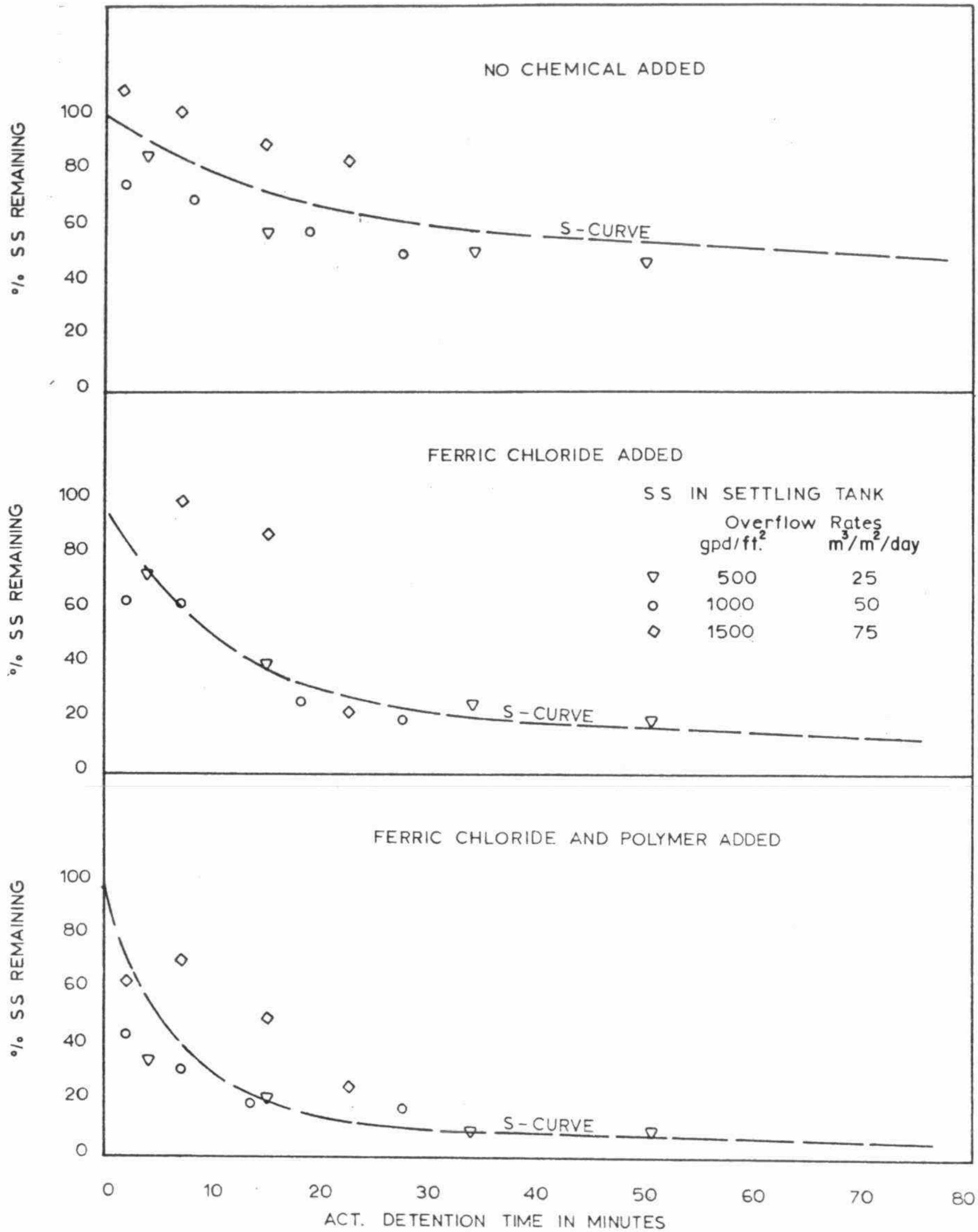


FIGURE 29. SETTLING BEHAVIOUR OF PHYSICAL-CHEMICAL FLOCS AT WINDSOR: Settling Model - Real tank

removal. (Note: because of the limitations of Equation 5, the effluent quality was estimated directly from S-, and C-curves, by superimposing one over the other with true dimensions). As the overflow rate increased further and the front of the C-curve penetrated more and more into the steeper portion of the S-curve, the effluent quality deteriorated more rapidly.

At Burlington, the situation was somewhat different. Although there were signs of short-circuiting, the effluent quality remained reasonably stable and better than that in Windsor. At an overflow rate of 2000 gpd/ft^2 or 100 m^3/m^2/day), about 20-25 percent of the flow received only 5-15 minutes of detention time, but the effluent quality did not seem to be affected as seriously as in Windsor. This was probably because of the following two reasons:

(i) The suspensions were already flocculated in the flocculating tank before they were discharged into the settling tank and consequently they settled relatively faster in the initial stages than those in Windsor.

(ii) The Burlington tank, because of its very small radius to depth ratio, can be characterized as an up-flow clarifier where the sweeping action of flocs, and possibly sludge blanket, played a significant role in the clarification and flocculation process, particularly with chemical addition. The formation of closely spaced horizontal profiles of suspended solids (sludge blanket) tends to support this thought (Figures 22, 23 and 24).

The performance of the tank is predictable, however, by the model using tg as a parameter.

Figures 28 and 29 provide supporting data to show that the Settling Model is applicable at any stage of settling inside the tank as well as at the outlet point. The figures further show that the inlet of the circular tank has a stronger influence than that of the rectangular tank, particularly at high overflow rates. This is evident from the fact that at 15000 gpd/ft^2 (75 m^3/m^2/day) overflow rate, there was practically no settling for the first 10-15 minutes, particularly without chemical addition.

10.2 Dispersion Model

The objective of this model was to study the effect of velocity and turbulence on the performance of settling tank. The model is based on Sutton's semi-empirical model (Sutton, 1932, 1934, 1947 twice), which has been modified to allow for the conditions in the settling tank. Sutton's model was adopted for this study because of its simplicity and successful use in atmospheric diffusion and dispersion of stack effluents in air pollution studies.

10.2.1 General form of model

The modifications applied to Sutton's model mainly consisted of the addition of some coefficients and dimensional factors to account for the physical features of the settling tanks. As a result, the model took the following general form:

$$S = \frac{K_1 Q^d EXP(-Y^2/C_x^{\ 2}\ X^a)}{C_x C_z U\ X^a} \left[EXP\left(\frac{K_2(Z-H)}{C_z^{\ 2}\ X^b}\right) + EXP\left(\frac{K_3(Z+H)}{C_z^{\ 2}\ X^b}\right) \right] \qquad (6)$$

where: C_x - eddy coefficient in flow direction $= \left[\frac{M}{U^N} \left(\frac{(\overline{V'})^2}{U^2} \right)^{1-N} \right]^{\frac{1}{2}}$

C_z - eddy coefficient in vertical direction $= \left[\frac{M}{U^N} \left(\frac{(\overline{W'})^2}{U^2} \right)^{1-N} \right]^{\frac{1}{2}}$

S - concentration of suspended solids (mg/l),

Q - suspended solids loading (kg/day),

X, Y, Z - coordinates measured, respectively, horizontally in the direction of flow, across the tank and vertically downward (m),

H - depth of baffle board (or centre ring) below the water surface (m),

U - mean resultant velocity (mm/sec) (calculated from velocities in X,Y, Z directions),

V', W' - eddy velocities in flow (horizontal) and vertical direction, respectively (mm/sec).

K_1, K_2, K_3, - constants,

N, M, a, b, d - constants.

10.2.1.1 Eddy velocity. The current velocity consists of a mean value together with a superimposed oscillatory component. If V, W are the velocity components in the flow (horizontal) and vertical direction respectively, then:

$$V = \overline{V} \quad V', \qquad \overline{V'} = 0$$

$$W = \overline{W} \quad W', \qquad \overline{W'} = 0$$

where the bars indicate mean value with respect to time.
Hence, eddy velocities are calculated as follows:

$$V' = V - \overline{V}$$

$$W' = W - \overline{W}.$$

10.2.2 Numerical form of model

Equation 6 was solved by the nonlinear least square method using the data for ferric chloride and polymer addition. The values of constants for the three plants were worked out to be as follows:

Location	K_1	K_2	K_3	a	b	d
Burlington	43.86	0.34	0.072	0.10	0.1	0.2
Sarnia	20.22	0.15	0.120	0.35	0.1	0.2
Windsor	18.38	0.09	0.055	0.24	0.1	0.2

The eddy coefficients were evaluated as follows:

$$c_x^{\ 2} = \frac{6}{U^{0.9}} \left[\frac{(\overline{V'})^2}{U^2}\right]^{0.1}$$

$$c_z^{\ 2} = \frac{6}{U^{0.9}} \left[\frac{(\overline{W'})^2}{U^2}\right]^{0.1}$$

Because of the symmetry of the data in the direction of Y, the factor containing Y in Equation 6 was omitted.

10.2.3 Performance parameters

Equation 6 shows that the concentration of suspended solids at any point in the settling tanks mainly depends on the strength of source or suspended solids loading (Q), velocity (U), and turbulence level (V', W'). From the analysis of the data from the three plants, the following performance parameters (eddy coefficients) were developed which are functions of velocity U:

$$C_x = \left[\frac{6}{U^{1.1}} \quad (4.69 + 0.024\ U^2) \quad 0.1\right]^{\frac{1}{2}}$$

$$C_z = \left[\frac{6}{U^{1.1}} \quad (3.23 + 0.001\ U^2) \quad 0.1\right]^{\frac{1}{2}}$$

10.2.4 Results

Figures 30, 31 and 32 show the comparison between the concentration of suspended solids observed and predicted by the model at various overflow rates with ferric chloride plus polymer addition, at WTC Burlington, Windsor and Sarnia, respectively.

Figure 33 shows the effect of the overflow rate on eddy coefficient at WTC Burlington, Windsor and Sarnia.

Figure 34 shows the relationship between eddy coefficient and suspended solids removal.

Figure 35 shows the relationship between eddy coefficient and average velocity.

Figure 36 shows the relationship between horizontal eddy coefficient (C_x) and vertical eddy coefficient (C_z).

Table 11 gives average values of eddy coefficients and suspended solids removal at various overflow rates, at WTC Burlington, Windsor and Sarnia (ferric chloride plus polymer added).

Table 12 shows comparison of dispersion model and real tank performance at various overflow rates at WTC, Sarnia and Windsor (ferric chloride plus polymer added).

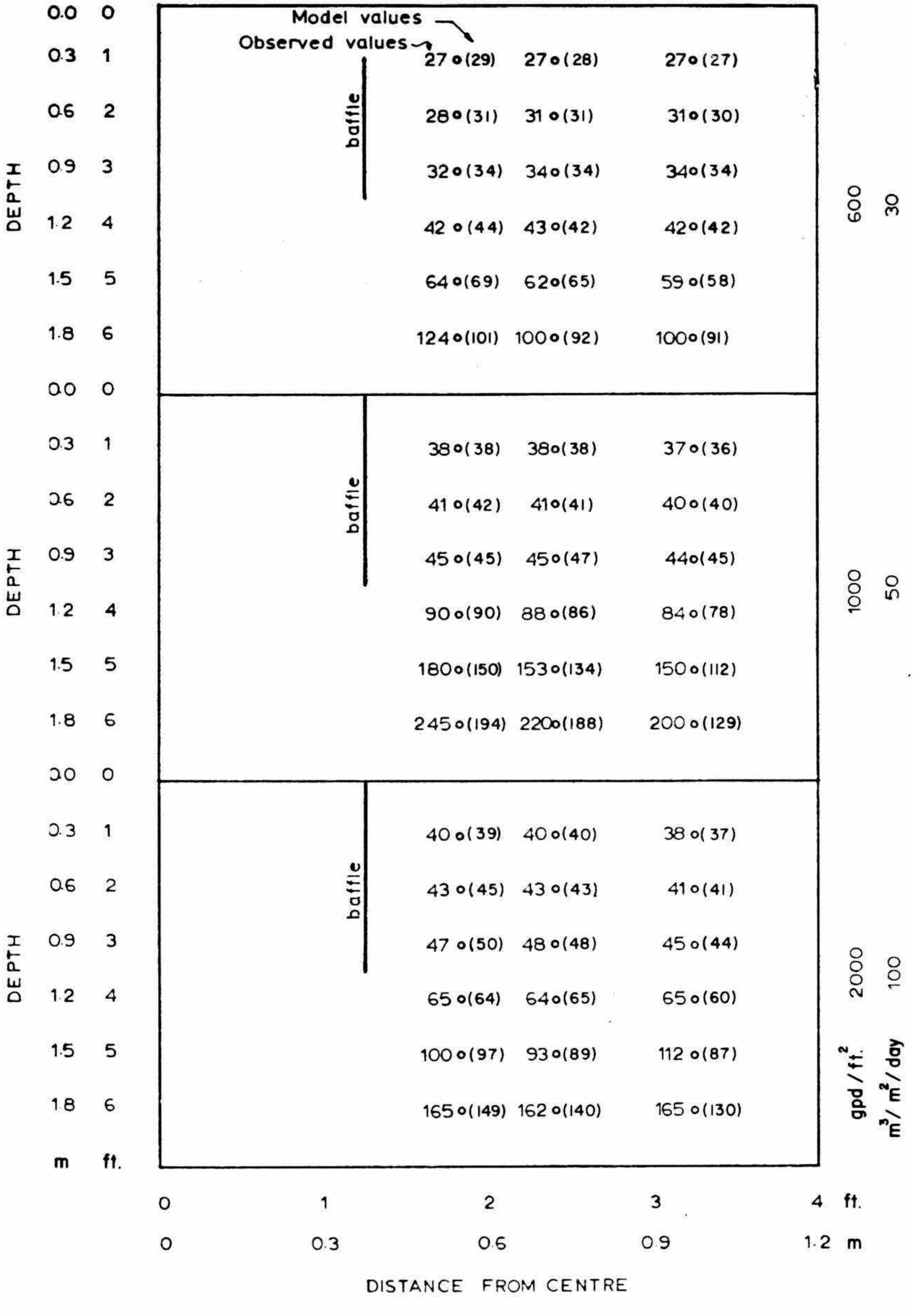


FIGURE 30. DISPERSION MODEL - SETTLING TANK AT BURLINGTON

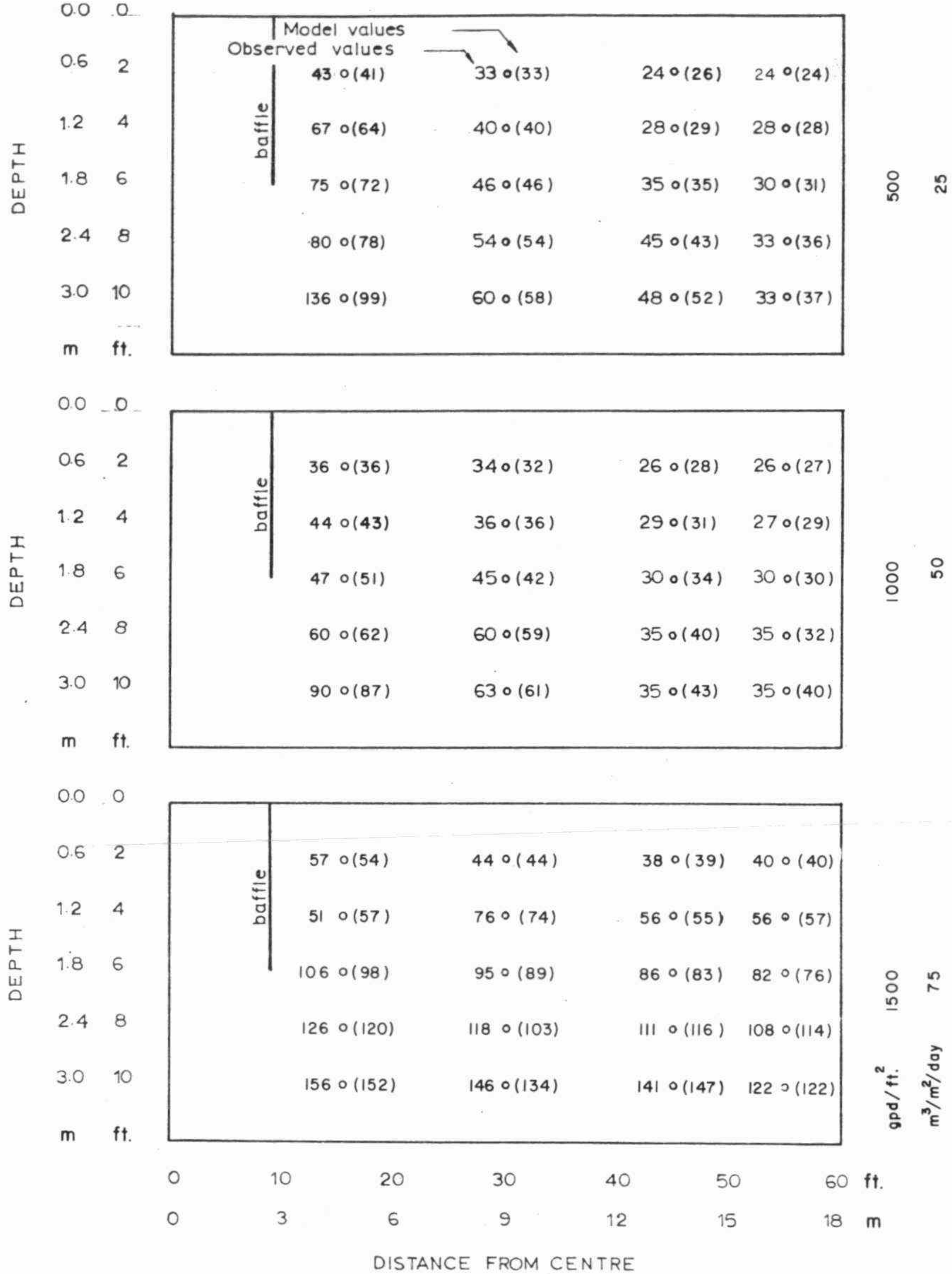


FIGURE 31 . DISPERSION MODEL - SETTLING TANK AT WINDSOR

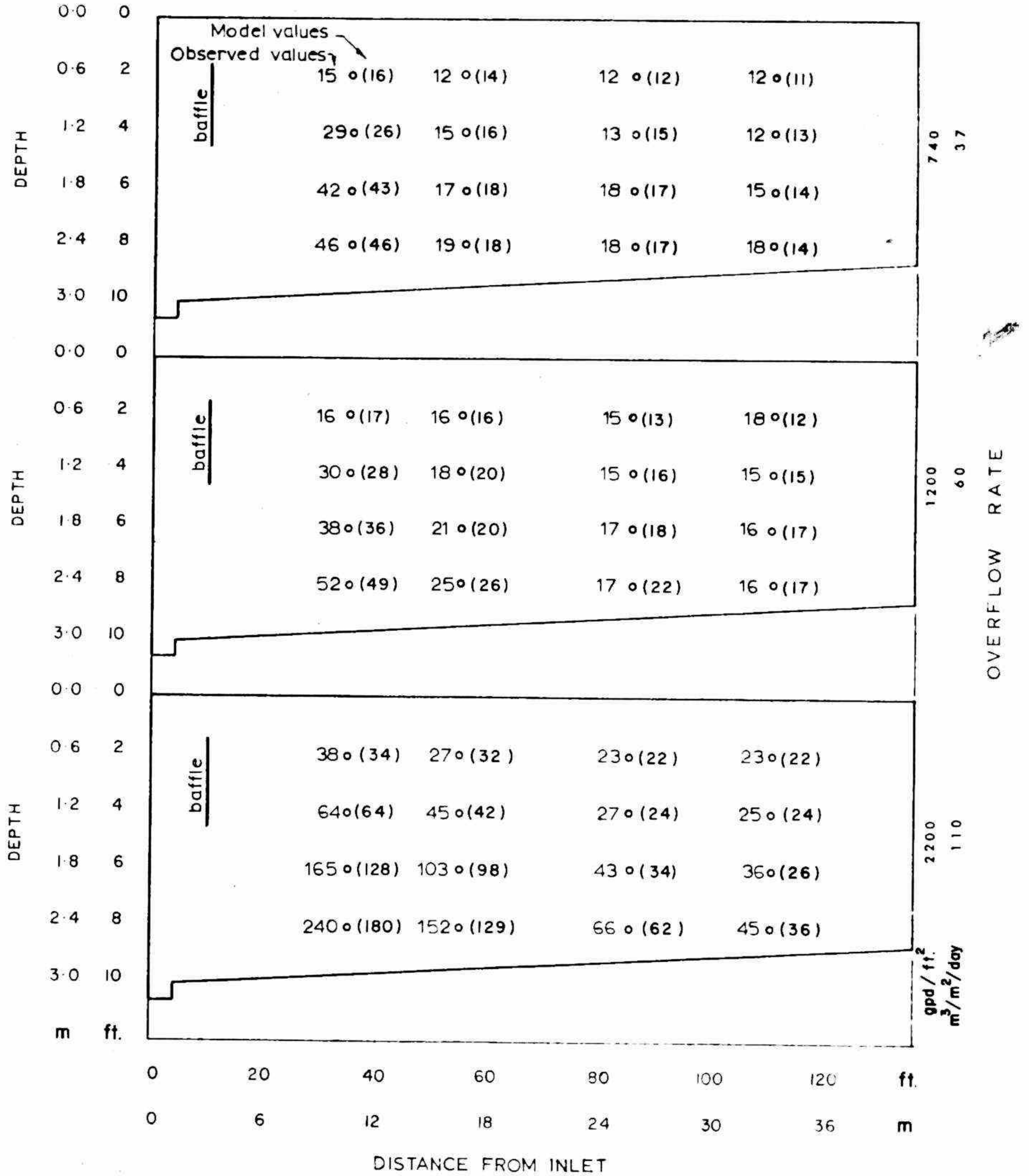


FIGURE 32. DISPERSION MODEL - SETTLING TANK AT SARNIA

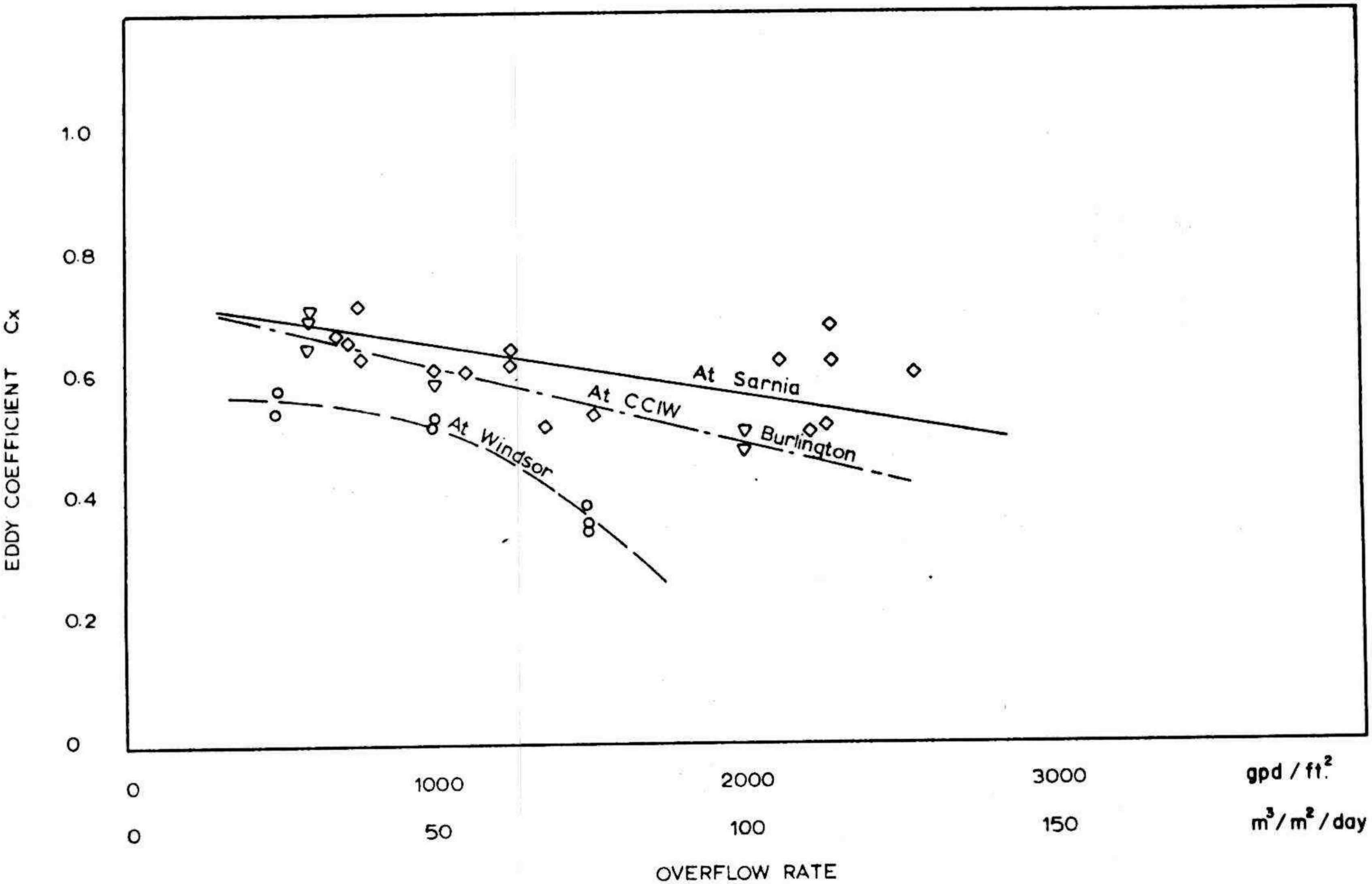


FIGURE 33. EFFECT OF OVERFLOW RATE ON EDDY COEFFICIENT C_x

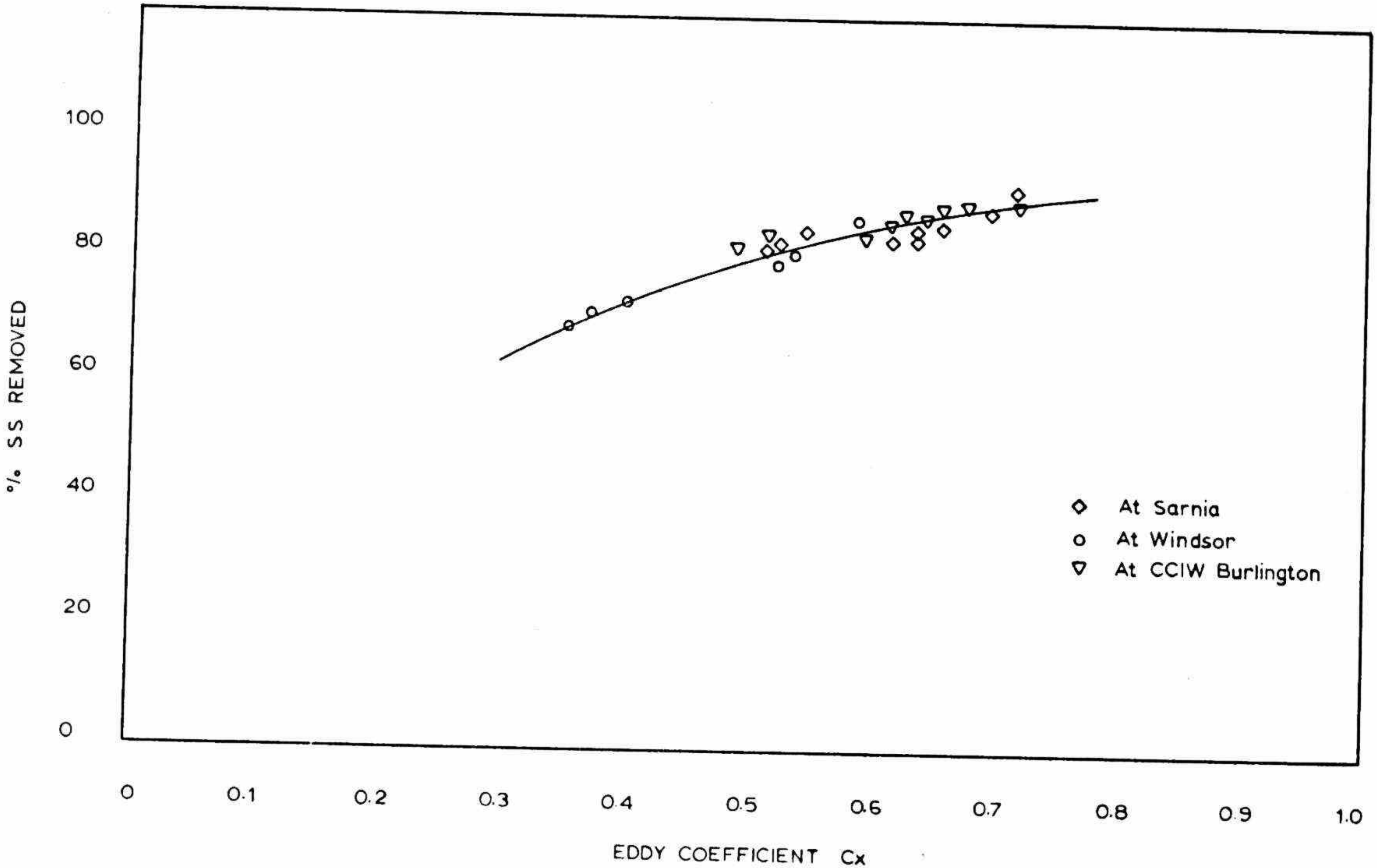


FIGURE 34. EFFECT OF EDDY COEFFICIENT C_x ON SUSPENDED SOLIDS REMOVAL

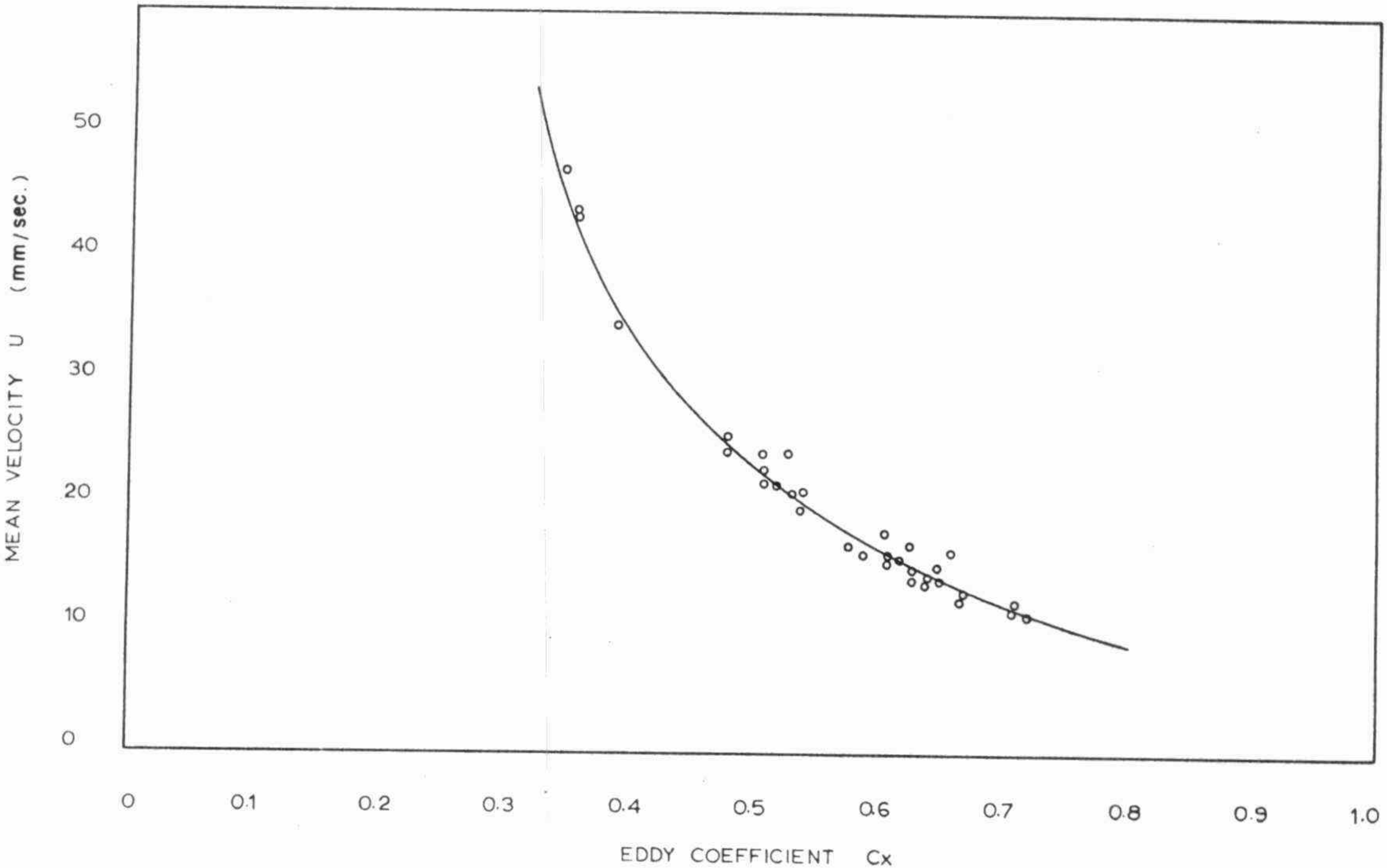


FIGURE 35 . EDDY COEFFICIENT C_X - MEAN VELOCITY

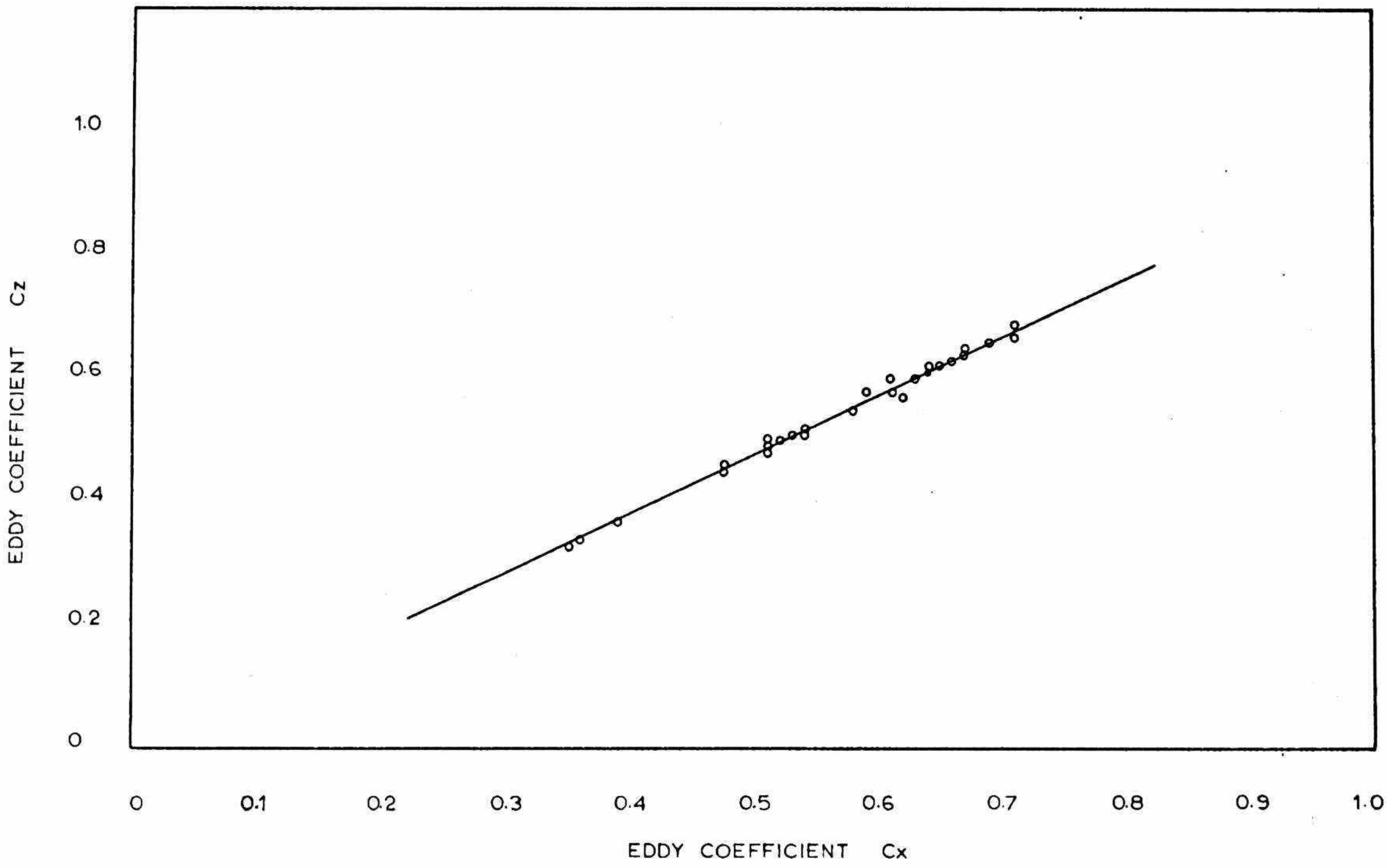


FIGURE 36. EDDY COEFFICIENT C_X - EDDY COEFFICIENT C_Z

TABLE 11. AVERAGE EDDY COEFFICIENTS AND SUSPENDED SOLIDS REMOVAL WITH FERRIC CHLORIDE PLUS POLYMER ADDITION

A. AT WTC BURLINGTON

Overflow Rate		Eddy Coefficient		SS Removal (Percent)
gpd/ft^2	$m^3/m^2/day$	C_x	C_z	
600	30	0.67	0.65	90
1000	50	0.62	0.59	88
2000	100	0.50	0.47	84

B. AT WINDSOR

Overflow Rate		Eddy Coefficient		SS Removal (Percent)
gpd/ft^2	$m^2/m^3/day$	C_x	C_z	
500	25	0.56	0.53	87
1000	50	0.53	0.51	81
1500	75	0.37	0.35	73

C. AT SARNIA

Overflow Rate		Eddy Coefficient		SS Removal (Percent)
gpd/ft^2	$m^3/m^2/day$	C_x	C_z	
740	37	0.68	0.65	90
1200	60	0.59	0.56	85
2200	110	0.60	0.57	85

TABLE 12. COMPARISON OF DISPERSION MODEL AND REAL TANK PERFORMANCE WITH FERRIC CHLORIDE PLUS POLYMER ADDITION

A. AT WTC BURLINGTON

Overflow Rate		Suspended Solids Remaining in Effluent, mg/l	
gpd/ft^2	m^3/m^2/day	Model	Real Tank
600	30	26	26
1000	50	33	36
2000	100	38	38

B. AT SARNIA

Overflow Rate		Suspended Solids Remaining in Effluent, mg/l	
gpd/ft^2	m^3/m^2/day	Model	Real Tank
740	37	15	14
1200	60	16	15
2200	110	25	24

C. AT WINDSOR

Overflow Rate		Suspended Solids Remaining in Effluent, mg/l	
gpd/ft^2	m^3/m^2/day	Model	Real Tank
500	25	26	26
1000	50	26	27
1500	75	45	46

10.2.5 Discussion of results

Figures 30 to 32 show that the concentration of suspended solids observed in settling tanks is in close agreement with the model values. Table 12 shows that the performance of the settling tank can be predicted with reasonable accuracy from the model.

The efficiency of settling tanks in removing suspended solids is directly related to eddy coefficient. As the value of eddy coefficient decreased from 0.70 to 0.50, the suspended solids removal efficiency decreased from about 90% to about 80% (Table 11). Only a few tests could be made between eddy coefficient values of 0.35 and 0.50, while no tests were carried out at the values above 0.7 and below 0.35, because of the operational limitations of the plants. Therefore, it is not possible to make any comments as to whether the results of this study could be applicable in those ranges.

From this model study, it is estimated that for 80% and better removal of suspended solids, the value of eddy coefficient C_x should be equal to or greater than 0.5 (implying average velocity equal to or less than 25 mm/sec) when ferric chloride plus polymer was added.

No relationship seems to exist between overflow rate and eddy coefficient from plant to plant. As shown in Figure 33, the value of C_x is 0.50 when overflow rate reaches about 1000 gpd/ft^2 (50 m^3/m^2/day) in Windsor, 2000 gpd/ft^2 (100 m^3/m^2/day) in Burlington, and probably about 3000 gpd/ft^2 (150 m^3/m^2/day) in Sarnia.

Figure 35 shows that the eddy coefficient is inversely related to resultant velocity U, and Figure 36 shows that C_x is directly related and approximately equal to C_z.

Analysis of the data for other chemical conditions (without chemical and with ferric chloride addition) is being carried out under a separate project. Considerable further work is required on the dispersion model, particularly as it applies to other plants, before this may become a useful tool.

11 PERFORMANCE PREDICTION AND TENTATIVE DESIGN GUIDELINES

The empirical settling model developed in this study is based on tests carried out at the treatment plants in Sarnia and Windsor and at the pilot plant in WTC Burlington, with and without the addition of chemicals to domestic wastewaters. It is thought to be applicable to other plants treating similar wastewaters. However, further verification is required.

11.1 Performance Prediction

The performance of primary clarifiers can be predicted from the following relationship:

$$S = \frac{S_o A}{(t_g)^n + A} \qquad \underline{\text{Settling Model}}$$

where: S = suspended solids remaining in effluent of settling tank, mg/l,

S_o = suspended solids in enffluent of settling tank, mg/l,

t_g = actual mean detention time, minutes, obtained from tracer studies,

n, A = constants of wastewater characteristics developed from settling column tests.

The values of the constants 'n' and 'A' for <u>domestic</u> wastewater, with and without chemical addition are:

Chemical Addition	n	A
No chemical	0.64	15.0
Ferric chloride (or alum)	0.90	7.5
Ferric chloride (or alum) plus Polymer	0.93	3.5

For other suspensions the constants must be determined from settling tests.

Limitations on use of settling model for domestic wastewater:

- t_i, time interval for initial indication of tracer in effluent should not be less than 15 minutes with chemical, and

30 minutes without chemical additions. This time is needed for flocculation, development and settling of flocs. For t_i values less than the above, calculate suspended solids remaining in effluent directly from S-curve and C-curve (see section 10.1).

- overflow rates should be less than 2000 gpd/ft^2 (100 m^3/m^2/day).

Operational constraints at the plants did not allow work at overflow rates in excess of 2000 gpd/ft^2 (110 m^3/m^2/day). Gray (1974) reported excessive carry-over of solids at the Sarnia Plant at an overflow rate of 2090 gpd/ft^2 (104 m^3/m^2/day), contrary to experience in this study. Gray did not use polymer. In this study at 2200 gpd/ft^2 (110 m^3/m^2/day) removal of suspended solids was 34, 72 and 87% without, with ferric chloride, and with ferric chloride plus polymer additions, respectively. However, an upper limit on overflow rate undoubtedly exists. Further work is required to establish these limits.

11.2 Tentative Design Guidelines

The following tentative guidelines are proposed for the design of primary clarifiers (horizontal flow clarifiers) treating domestic sewage:

Design flow Rate: Maximum daily flow (normally 1.5 - 2.0 x average daily flow).

Actual mean detention time (t_g):

30 minutes with chemical addition (ferric chloride plus polymer),

45 minutes without addition.

Minimum detention time (t_{10}):

(t_{10} time interval before 10% of quantity of the tracer added passes over the weir)

15 minutes with chemical addition (ferric chloride plus polymer),

30 minutes without chemical addition.

Overflow rate: less than 2000 gpd/ft^2 (100 m^3/m^2/day) under peak flow conditions,

Velocity: less than 8 ft/minute (40 mm/sec) under peak flow conditions.

Removal Efficiency: about 70% with ferric chloride addition,
about 85% with ferric chloride plus polymer addition,
about 40-50% without chemical addition.

Laboratory results and limited plant results on alum indicate that the above design guidelines may also be applicable for alum addition.

It is beyond the scope of this report to make recommendations regarding the geometric design of settling tanks (shape, length/width/depth or diameter/depth ratios, types and positions of baffles and weirs, etc.). The problem remains, therefore, how to choose actual tank dimensions to achieve a required actual detention time.

The use of these tentative guidelines will result in smaller settling tanks than would be required by current guidelines. The extent of decrease in sizes will depend on the hydraulic efficiency, e, which was previously defined as the ratio of actual mean detention time to theoretical detention time. The hydraulic efficiency of tanks studied under varying flow rates ranged from 0.30 (circular tank at Windsor) to 0.78 (rectangular tank at Sarnia).

12 FUTURE WORK

It is recommended that further work should be carried out on other treatment plants to confirm the findings of this study. Moreover, the scope of the research program should be extended to other important areas such as optimization of flocculation and sedimentation processes and improvement of hydraulic efficiency of settling tanks. These aspects of the investigation work are particularly important in the development of optimum functional design of a settling tank.

The recommended future work can be outlined as follows:

A. Checking the findings of this report at other treatment plants by collecting and studying additional data on,

   a) the hydraulic efficiency and performance of circular and rectangular tanks,
   b) the effect of overflow rate above 2000 gpd/ft^2 or 100 m^3/m^2/day on the settling tank performance,
   c) the overflow rate and velocity at which washout will occur,
   d) velocity and suspended solids profiles,
   e) similar plant scale studies for alum and lime flocs.

B. Optimization of functional design of settling tanks. This will include the study of the following factors:

   a) optimization of flocculation and sedimentation processes on a laboratory scale basis,
   b) concept development on the improvement of hydraulic efficiency of settling tanks by optimizing flow pattern, velocity distribution, Froude and Reynolds Numbers and inlet and outlet configurations,
   c) model and/or plant studies.

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